MUSE Data Reduction Workshop

Evelyn Johnston

Disclaimer: I am not a MUSE expert

- I am simply an experienced user of MUSE data
  - I was the MUSE fellow at ESO
  - I have reduced goodness knows how many MUSE datacubes
  - People keep asking me for help reducing MUSE data, and we usually manage to figure out the issue

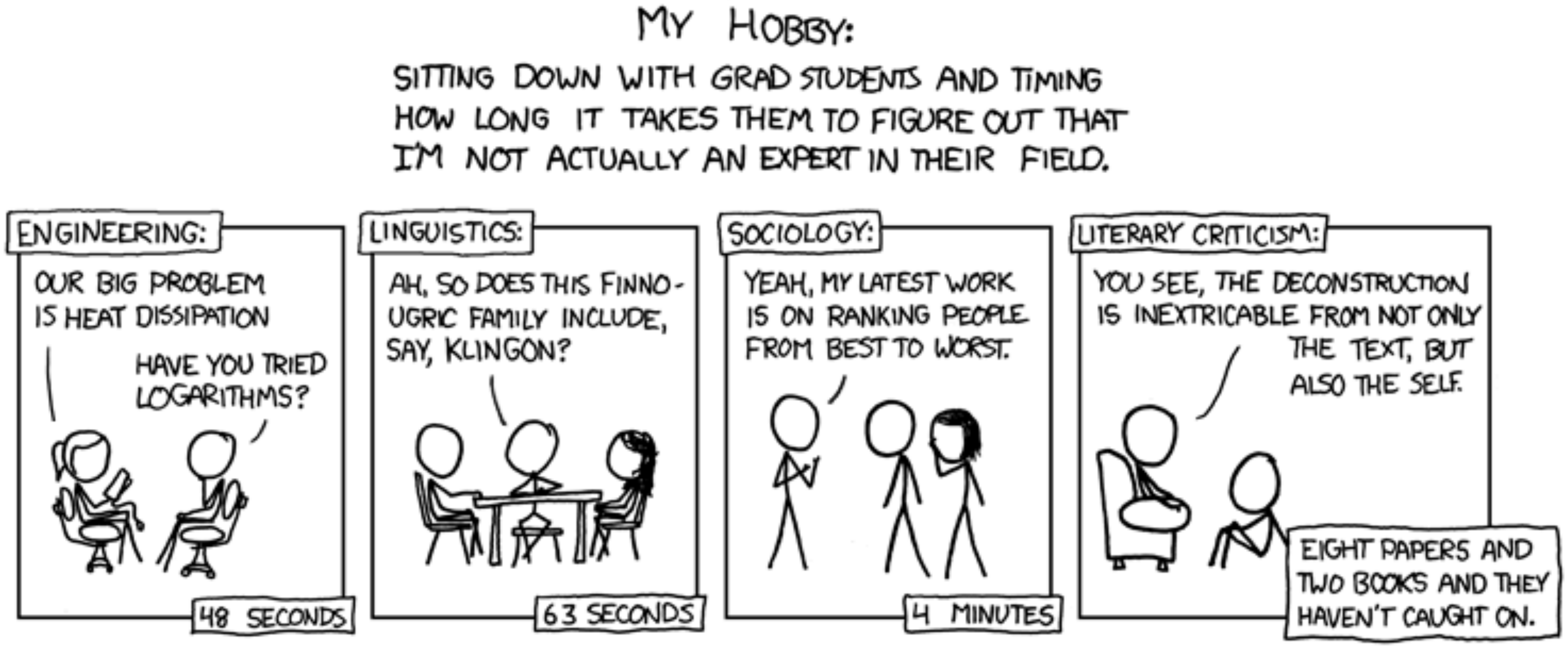


Image credit: xkcd.com/451/

Outline

- Introduction to Integral Field Spectroscopy
- Overview of MUSE
- Discussion of ESO Pipelines

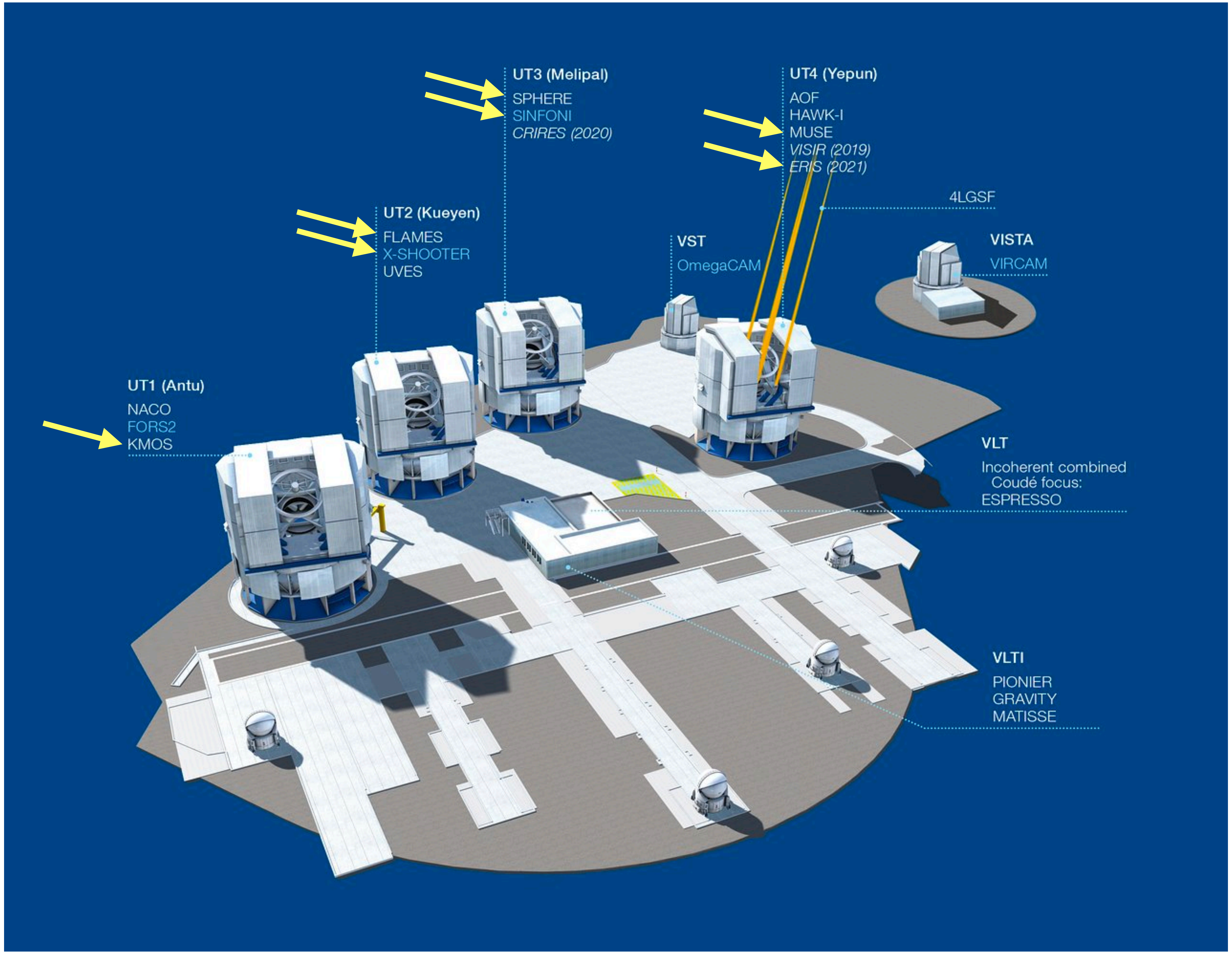
- MUSE data reduction
- What can go wrong when reducing MUSE data
- How to access MUSE data

Integral Field Spectroscopy

What is it and why should I care?

Integral Field Spectroscopy

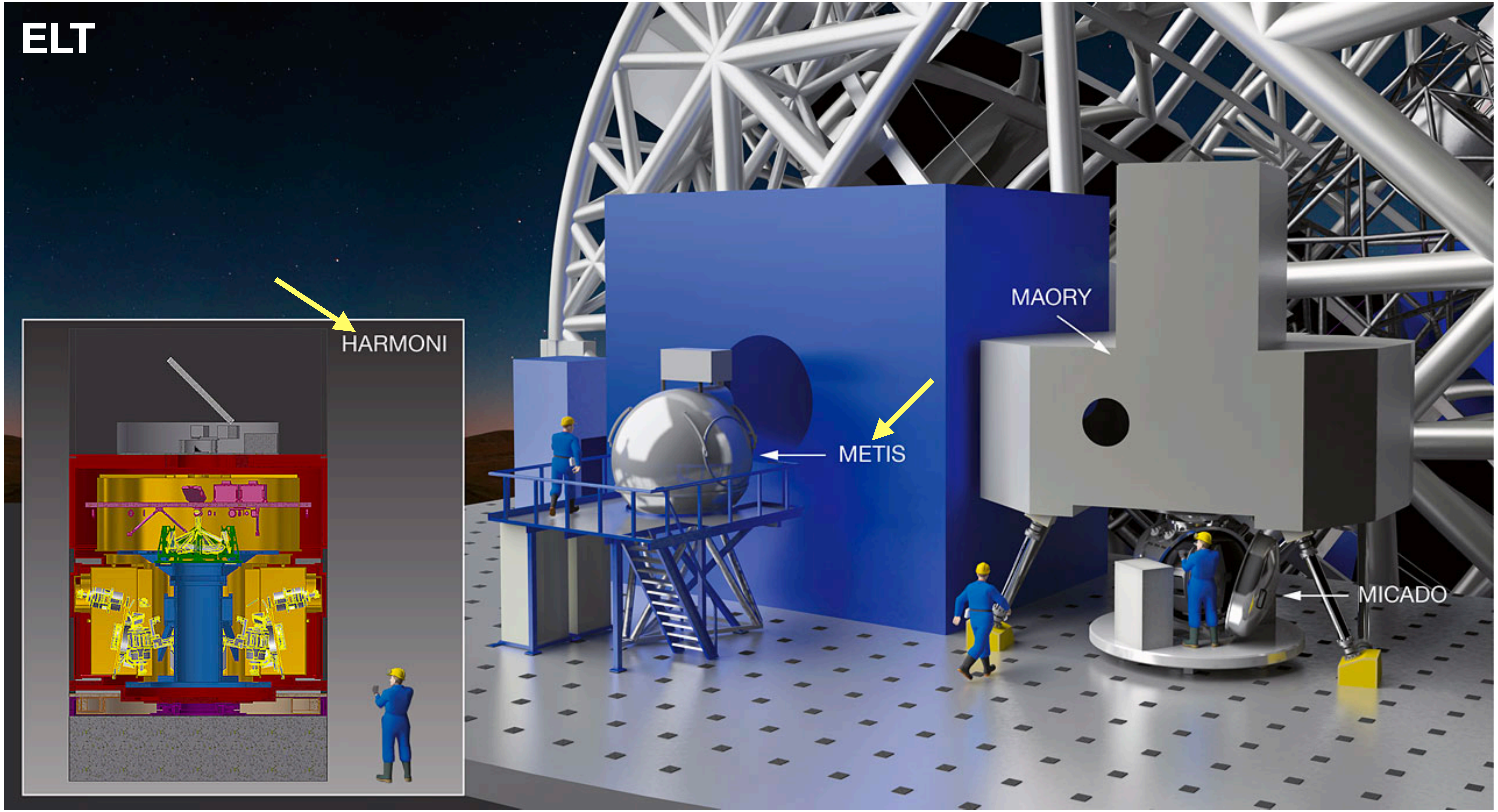
The importance of IFU spectroscopy, now and for the future



Credit: ESO

Integral Field Spectroscopy

The importance of IFU spectroscopy, now and for the future



Credit: NOVA/METIS/MAORY/MICADO/HARMONI

Integral Field Spectroscopy

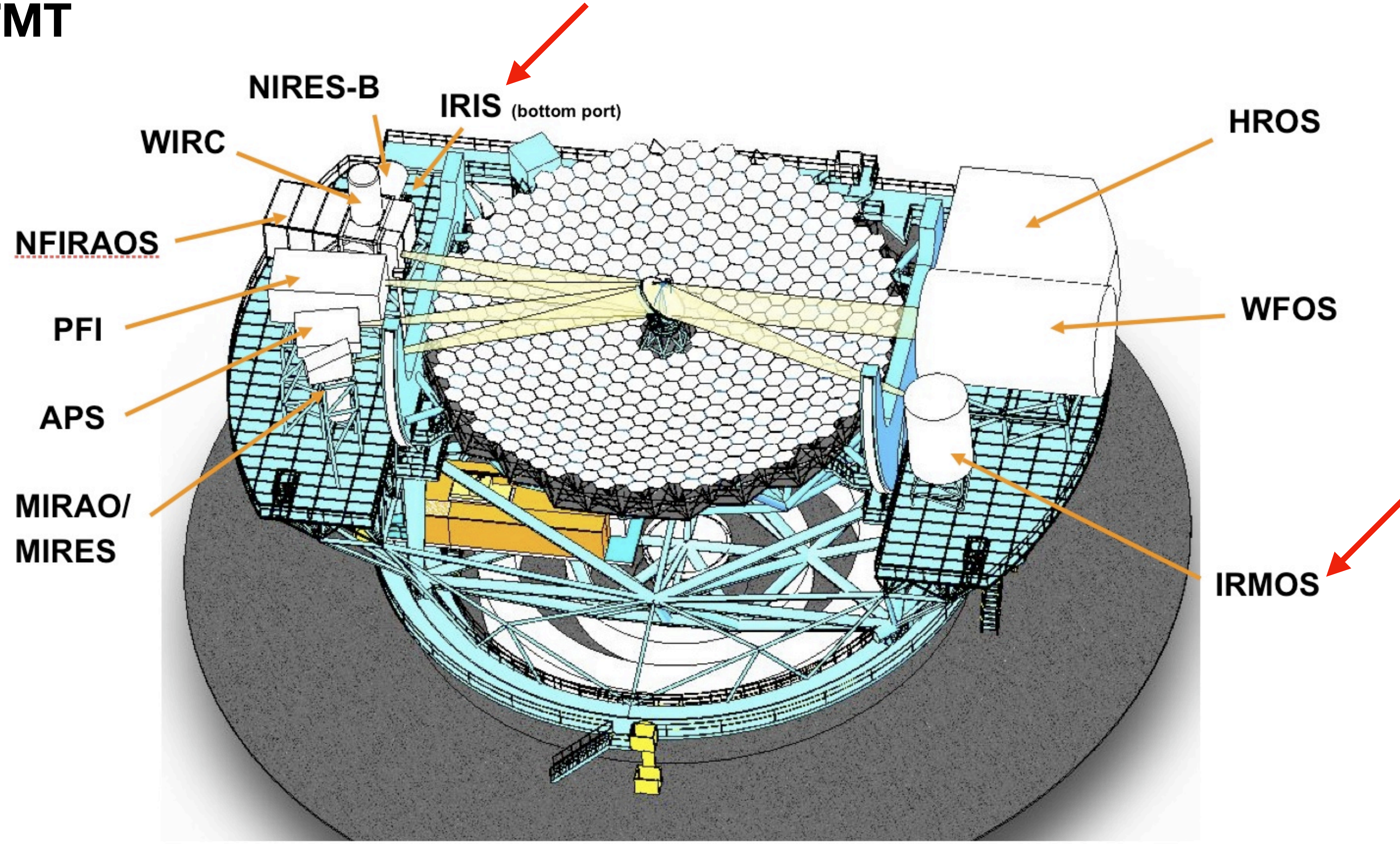
The importance of IFU spectroscopy, now and for the future

Credit: GMTO

Integral Field Spectroscopy

The importance of IFU spectroscopy, now and for the future

TMT



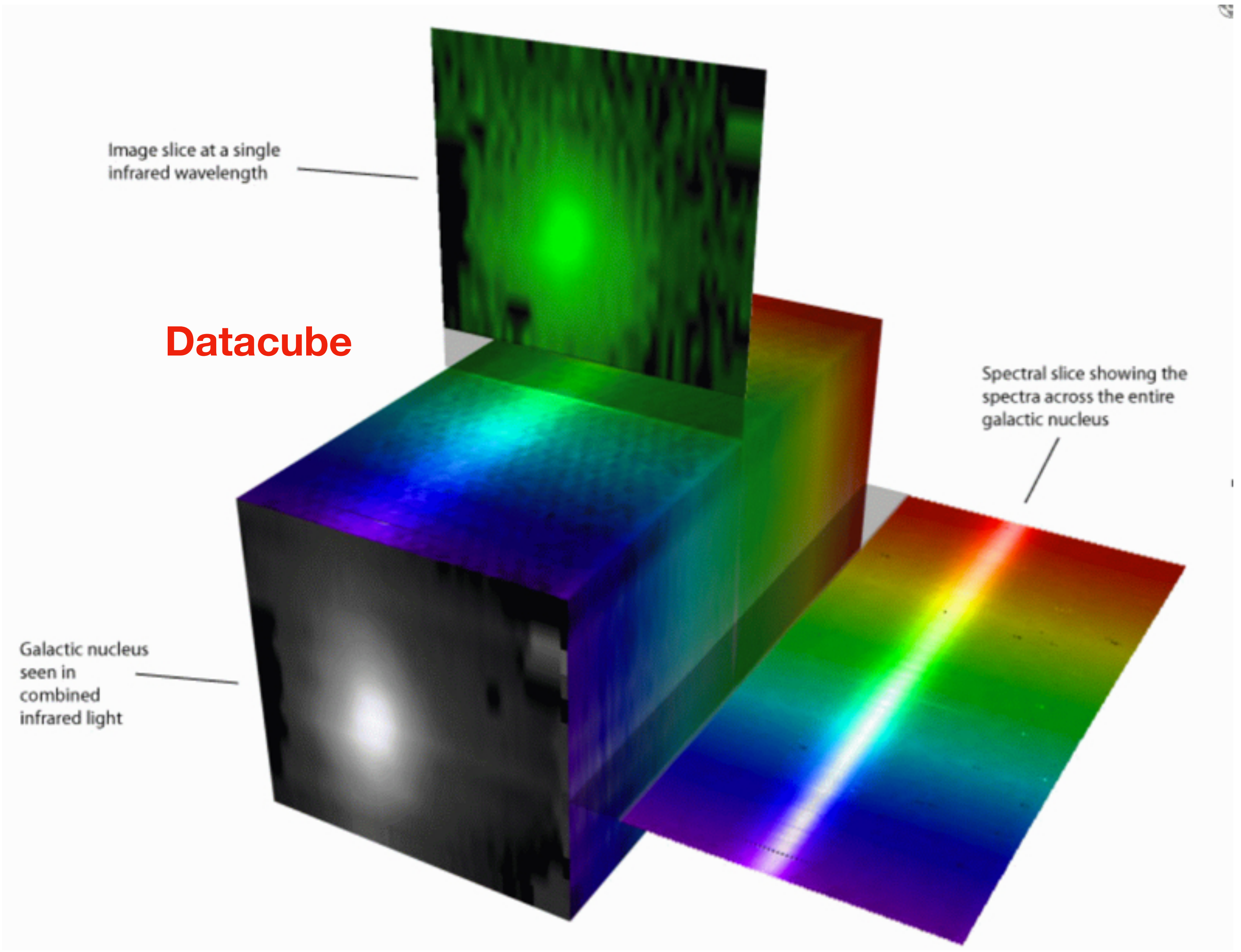
Credit: TMT

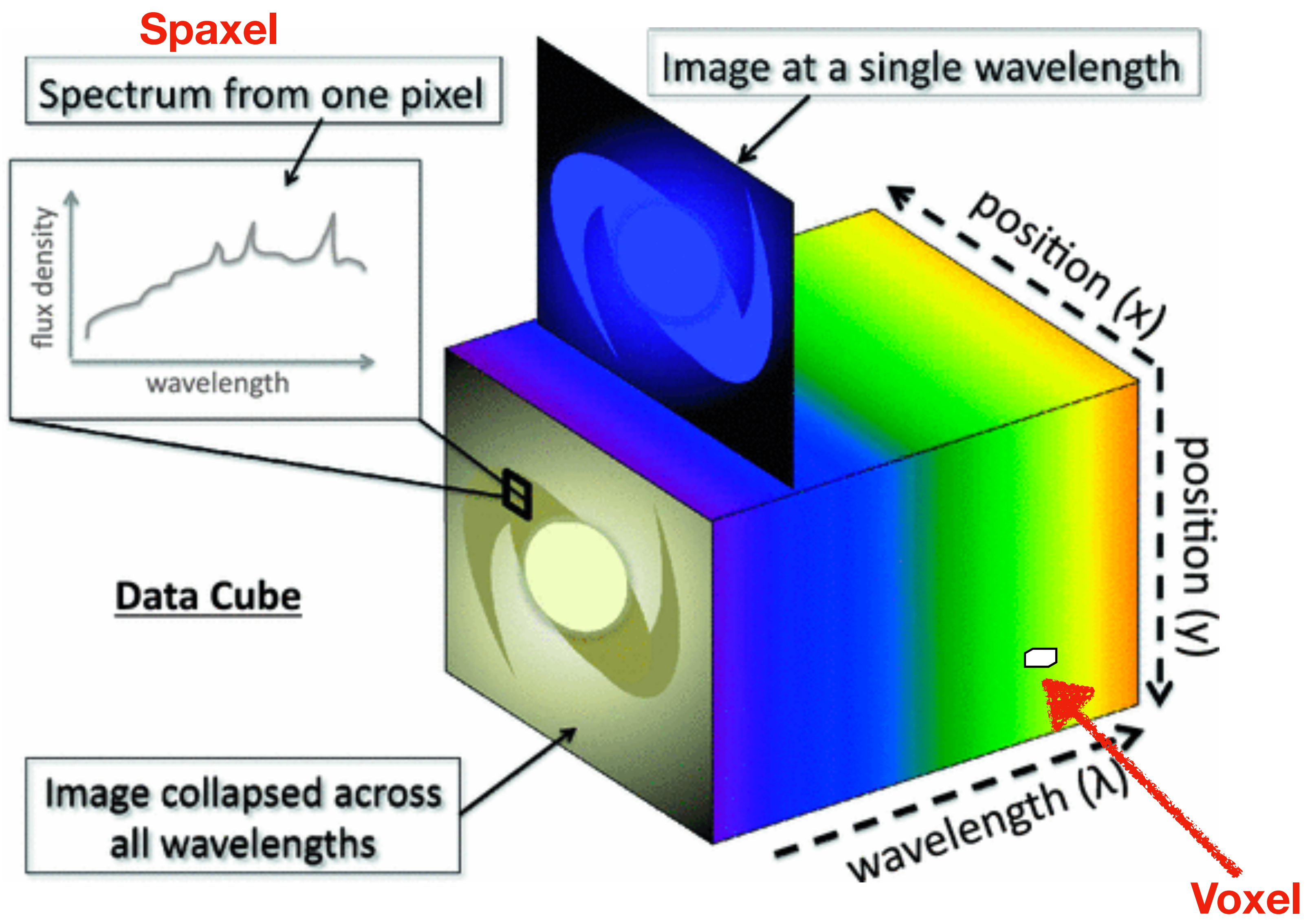
Integral Field Spectroscopy

What is it?

- Sometimes referred to as 3D spectroscopy
- The final product is a **datacube**.
- A datacube is simply a series of narrow-band images

- The FOV is sampled as small aperture elements called **spaxels**, each of which has an associated spectrum (spaxel=spectral pixel)
- Each element in a datacube is called a **voxel**





Integral Field Spectroscopy

Advantages

See example

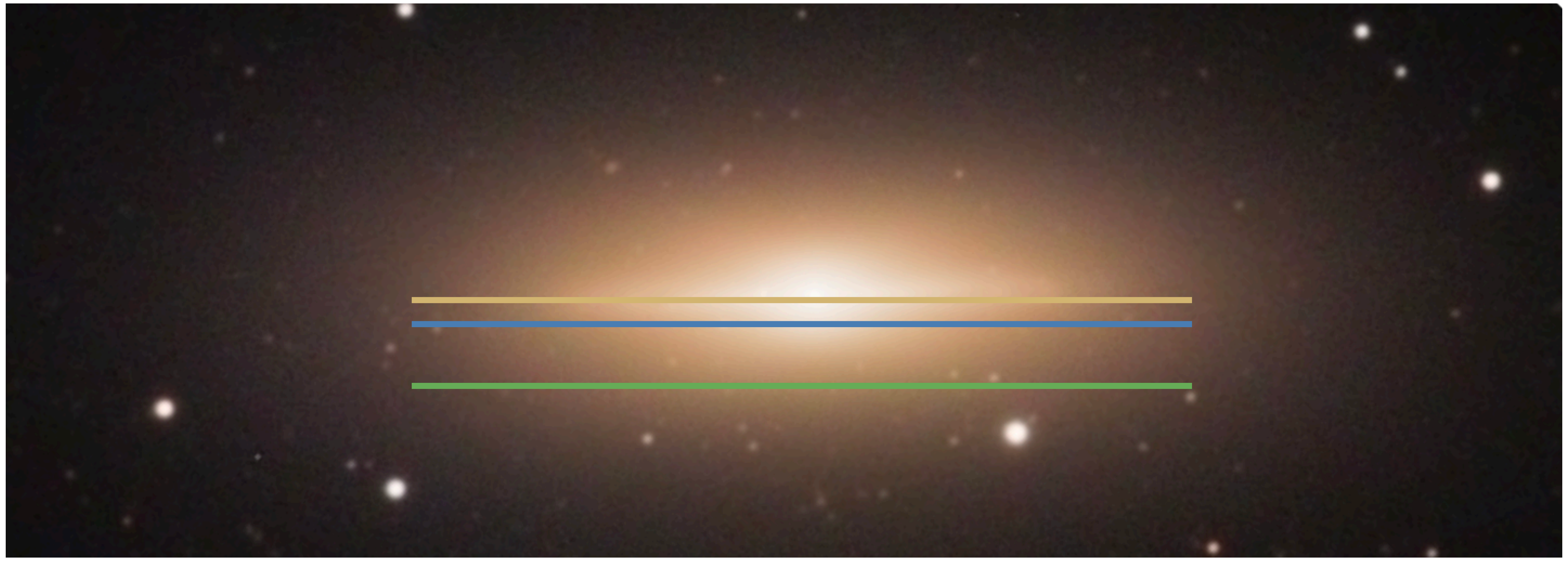
Integral Field Spectroscopy

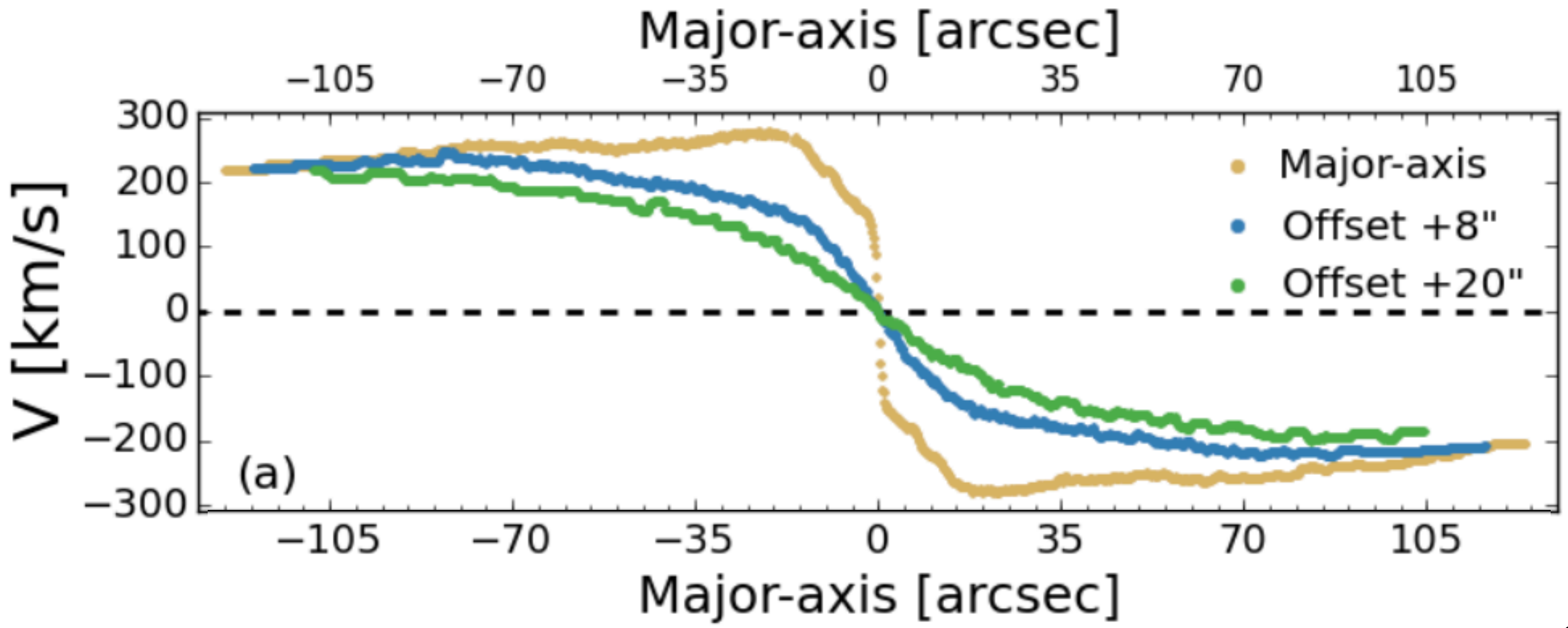
Advantages

- Observe the whole object

Long-slit spectoscopy

NGC 3115





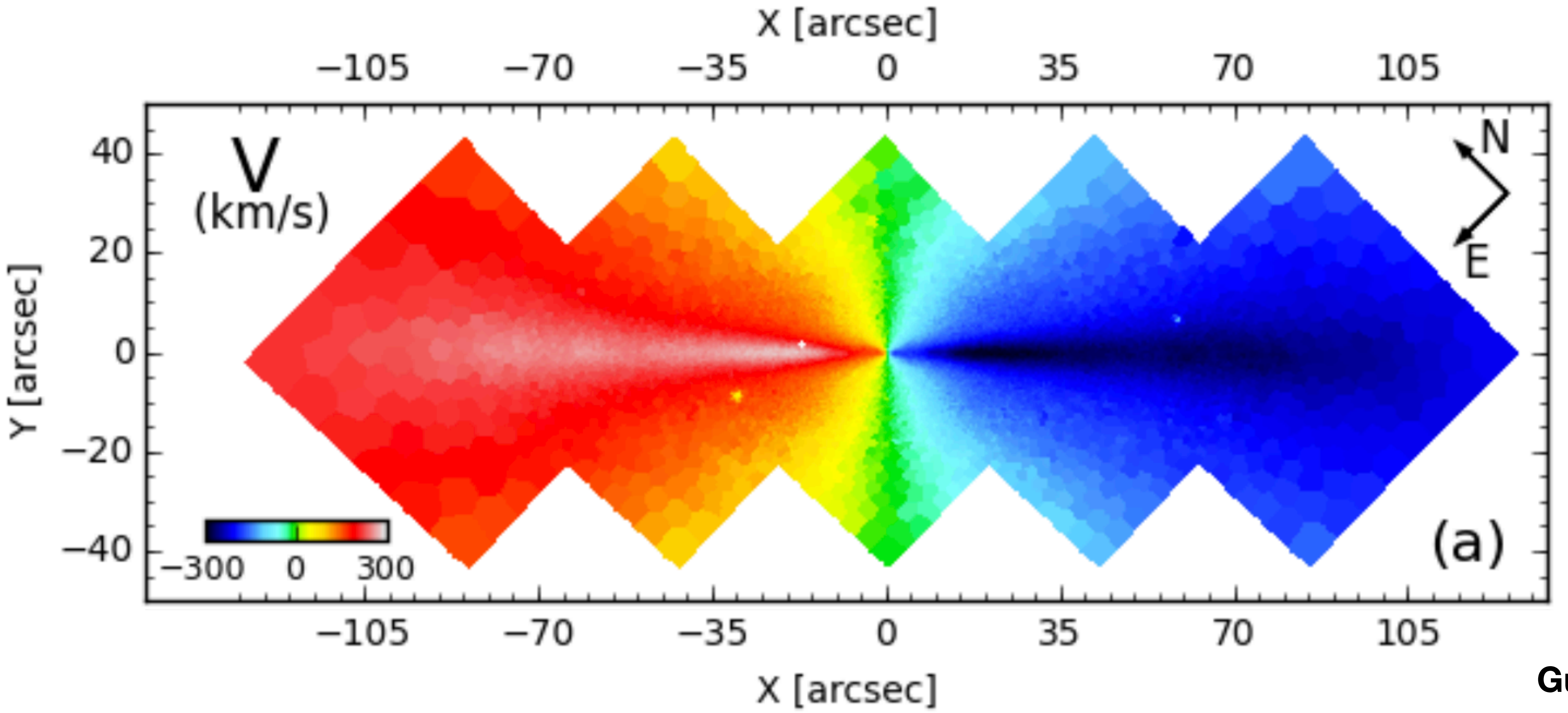
Guerou et al (2016)

Integral Field Spectroscopy
Advantages

- Observe the whole object

IFU

NGC 3115



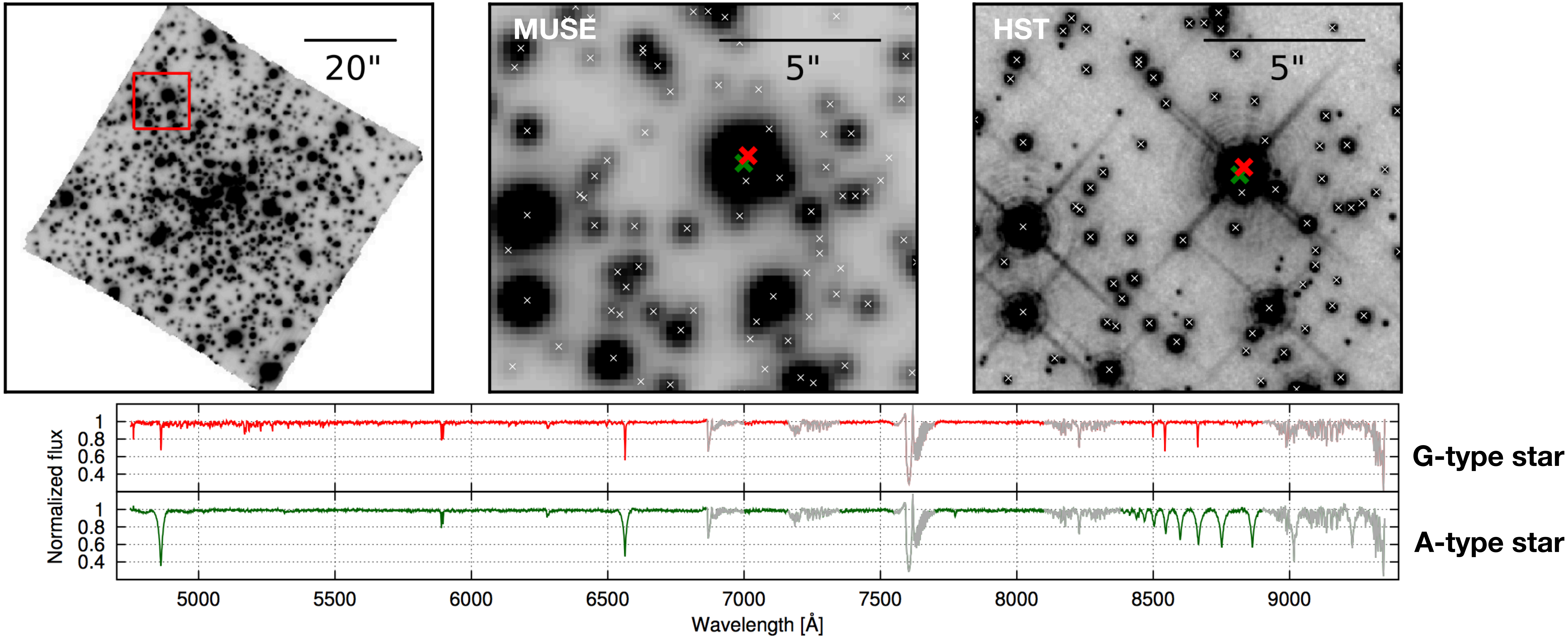
Guerou et al (2016)

Integral Field Spectroscopy

Advantages

- Deblend overlapping objects

NGC 6397



Husser et al (2016)

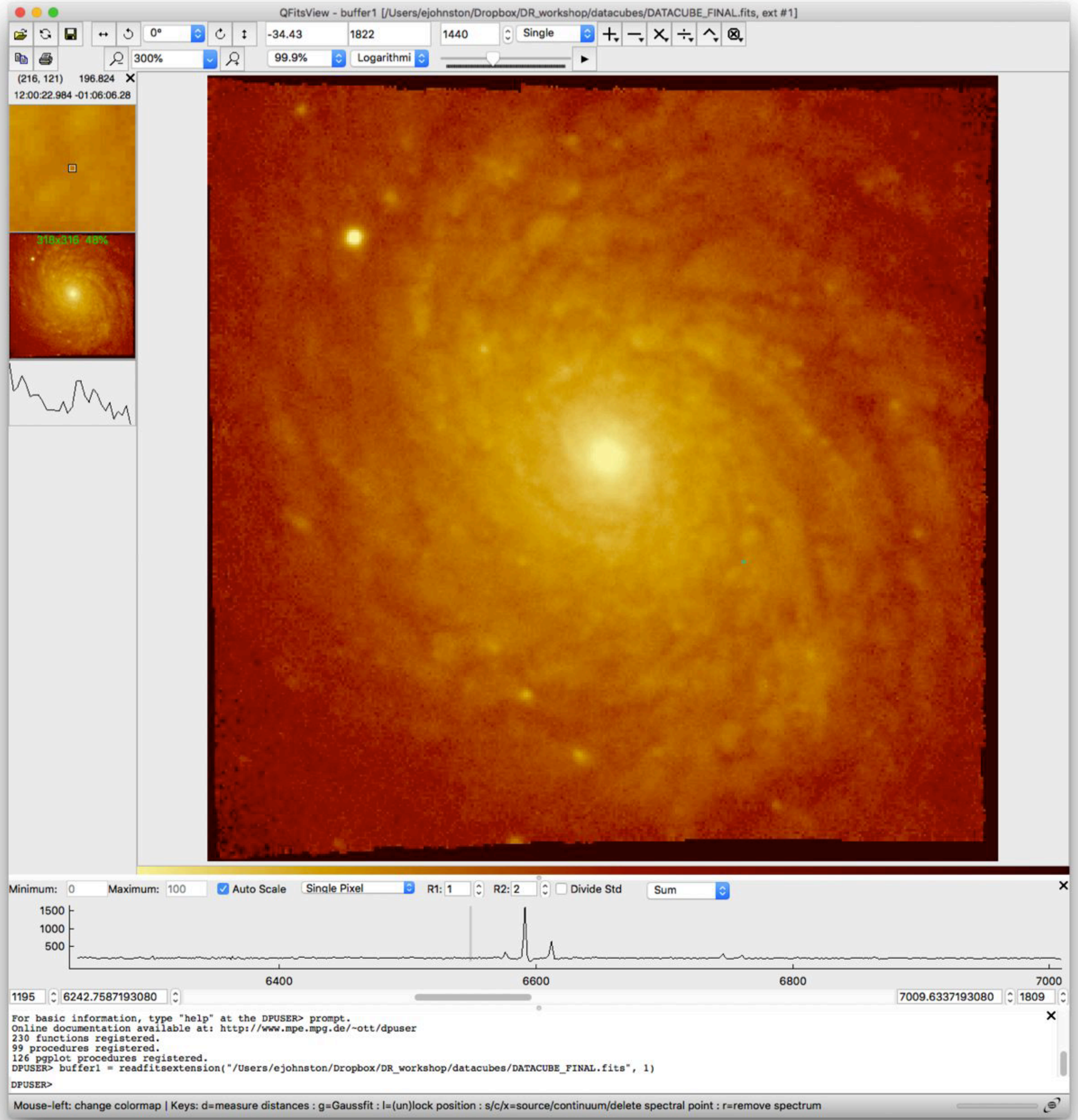
Integral Field Spectroscopy

Advantages

See example

Integral Fi

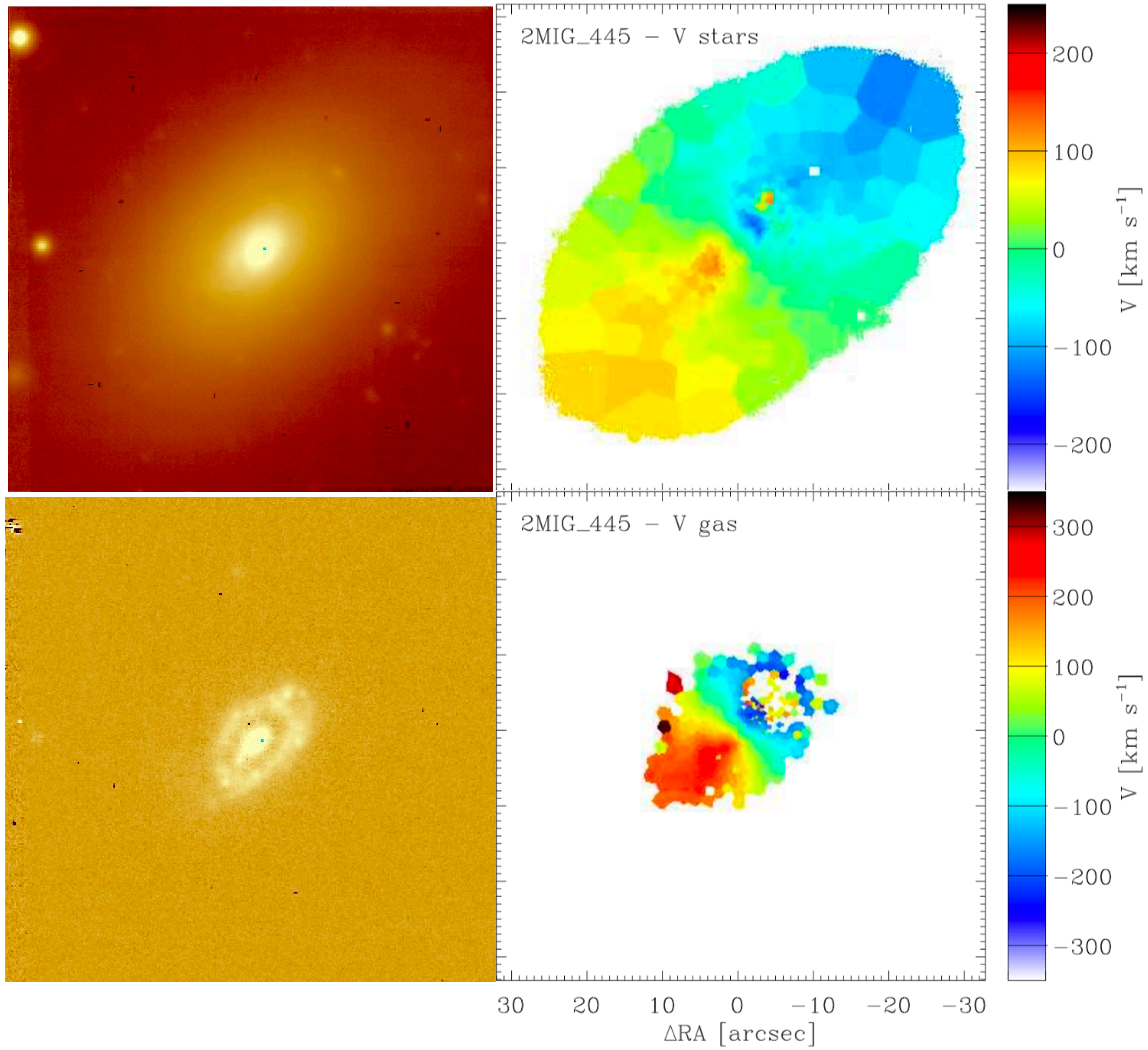
Advantages



Integral Field Spectroscopy

Example analyses

Stellar and Gas Kinematics



Coccato et al (submitted)

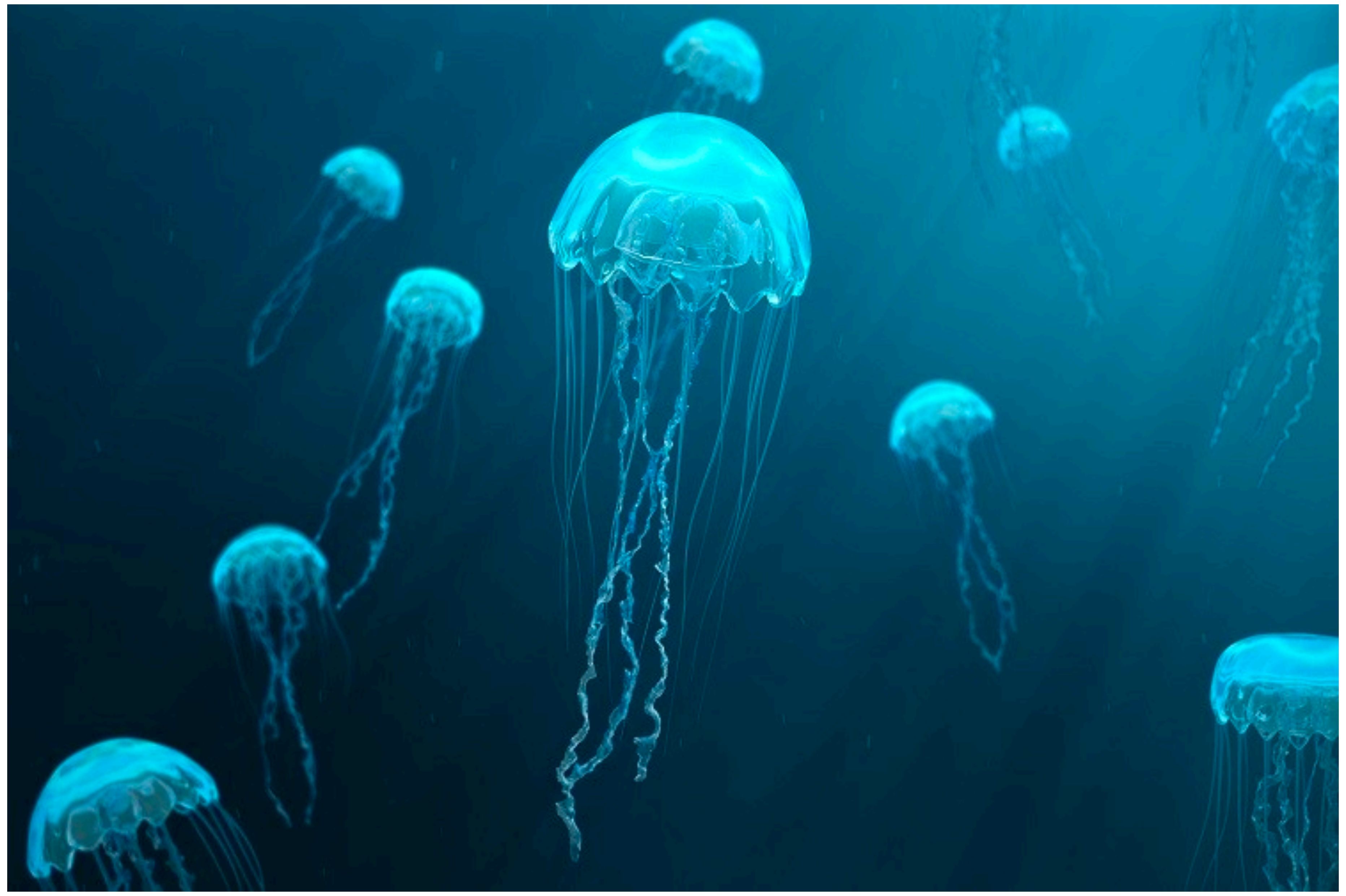
Integral Field Spectroscopy

Example analyses

Gas Stripping

Image credit: ESO/GASP collaboration

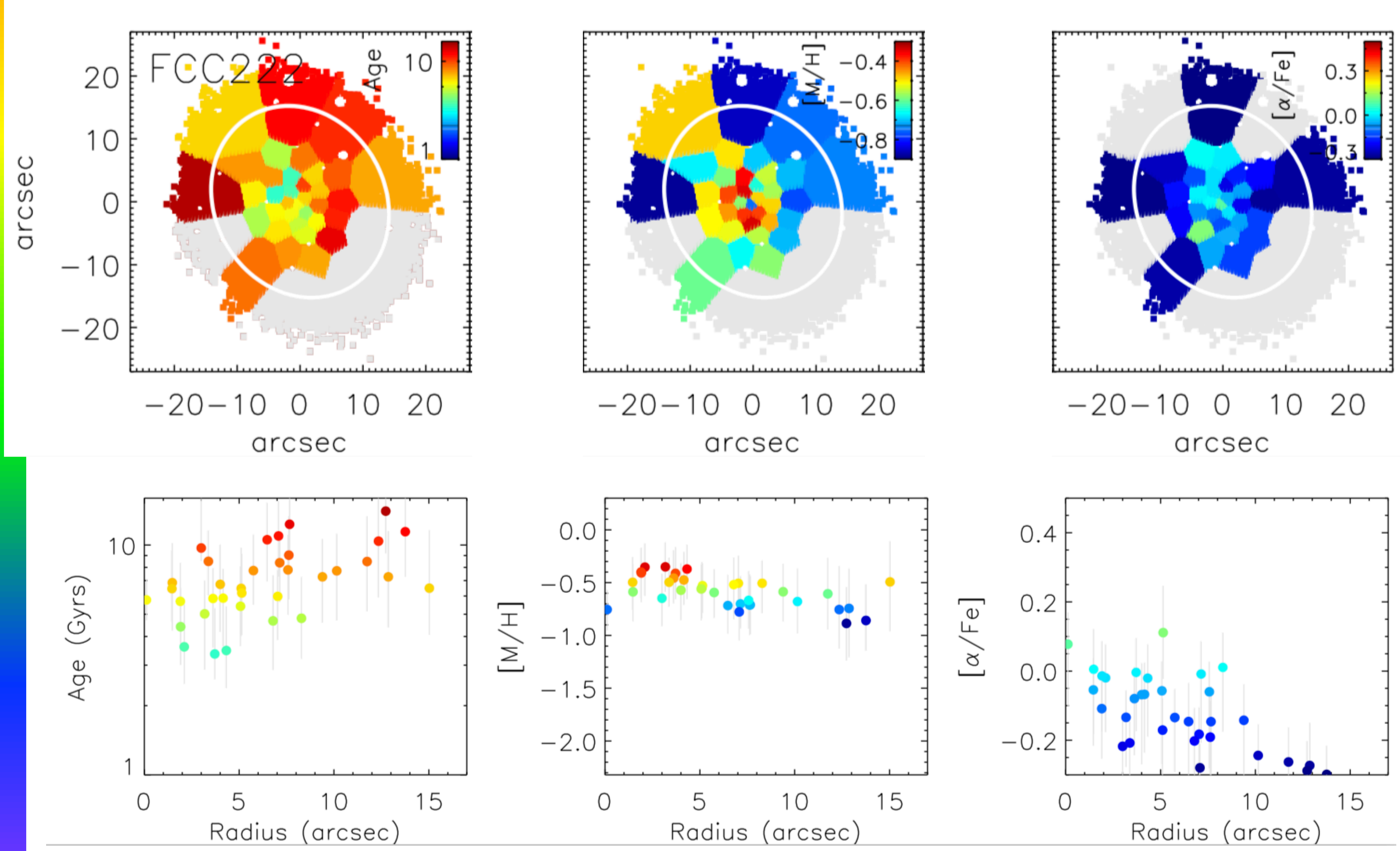
Also known as Jellyfish Galaxies



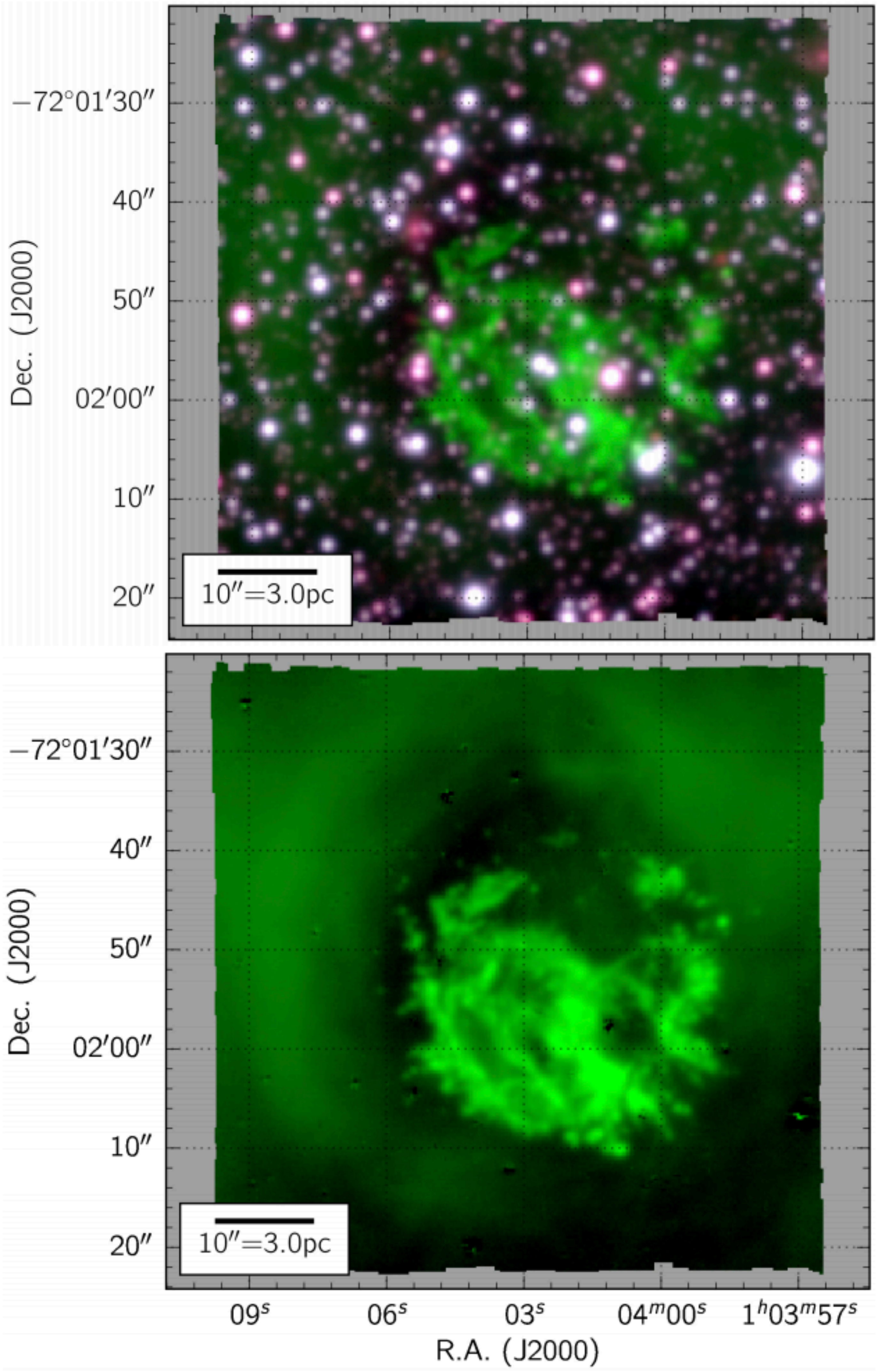
Integral Field Spectroscopy

Example analyses

Stellar Populations



Mapping SNe Remnants

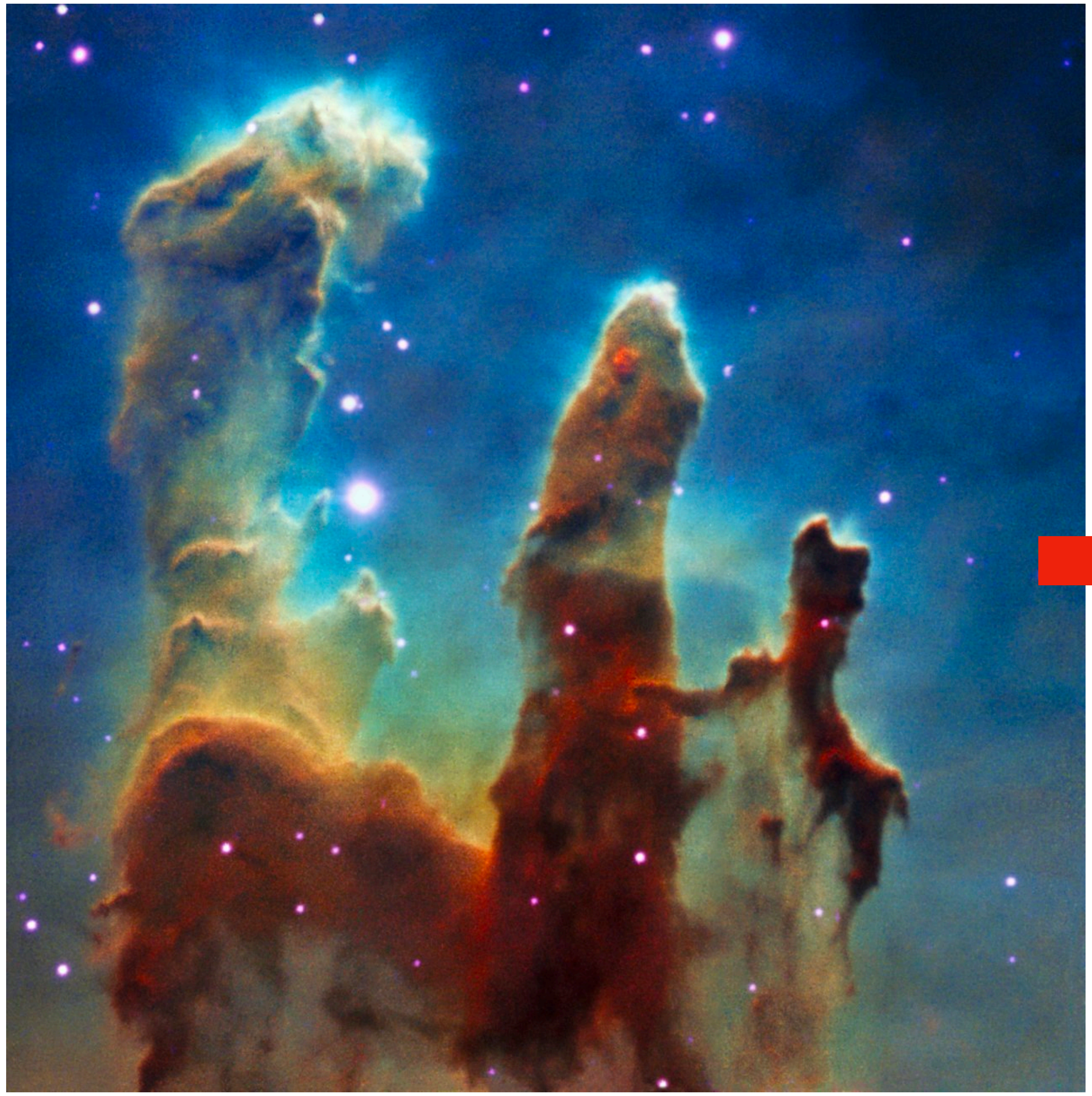


Vogt et al (2017)

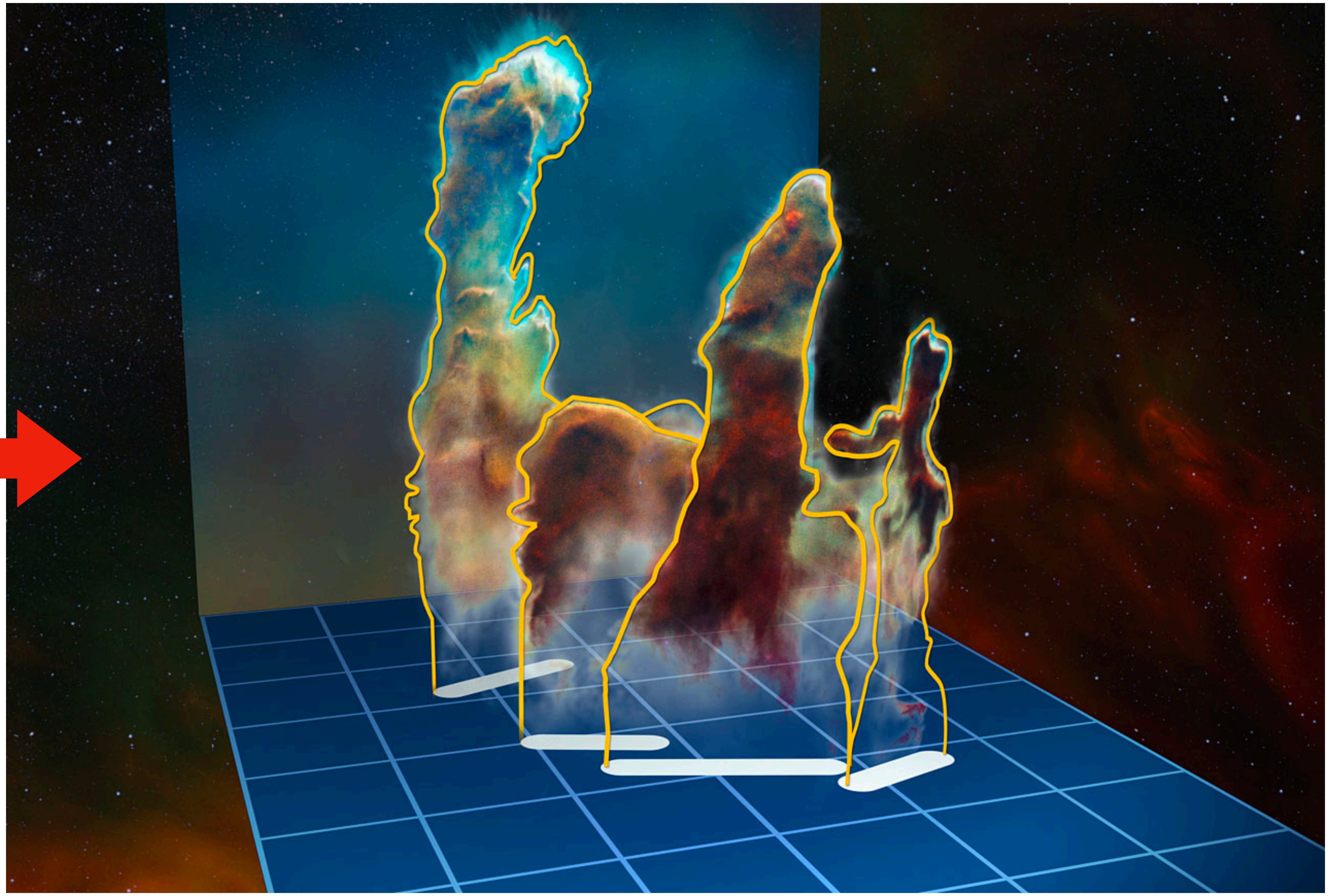
Integral Field Spectroscopy

Example analyses

Determine 3D positions of targets in the FOV



Credit: ESO

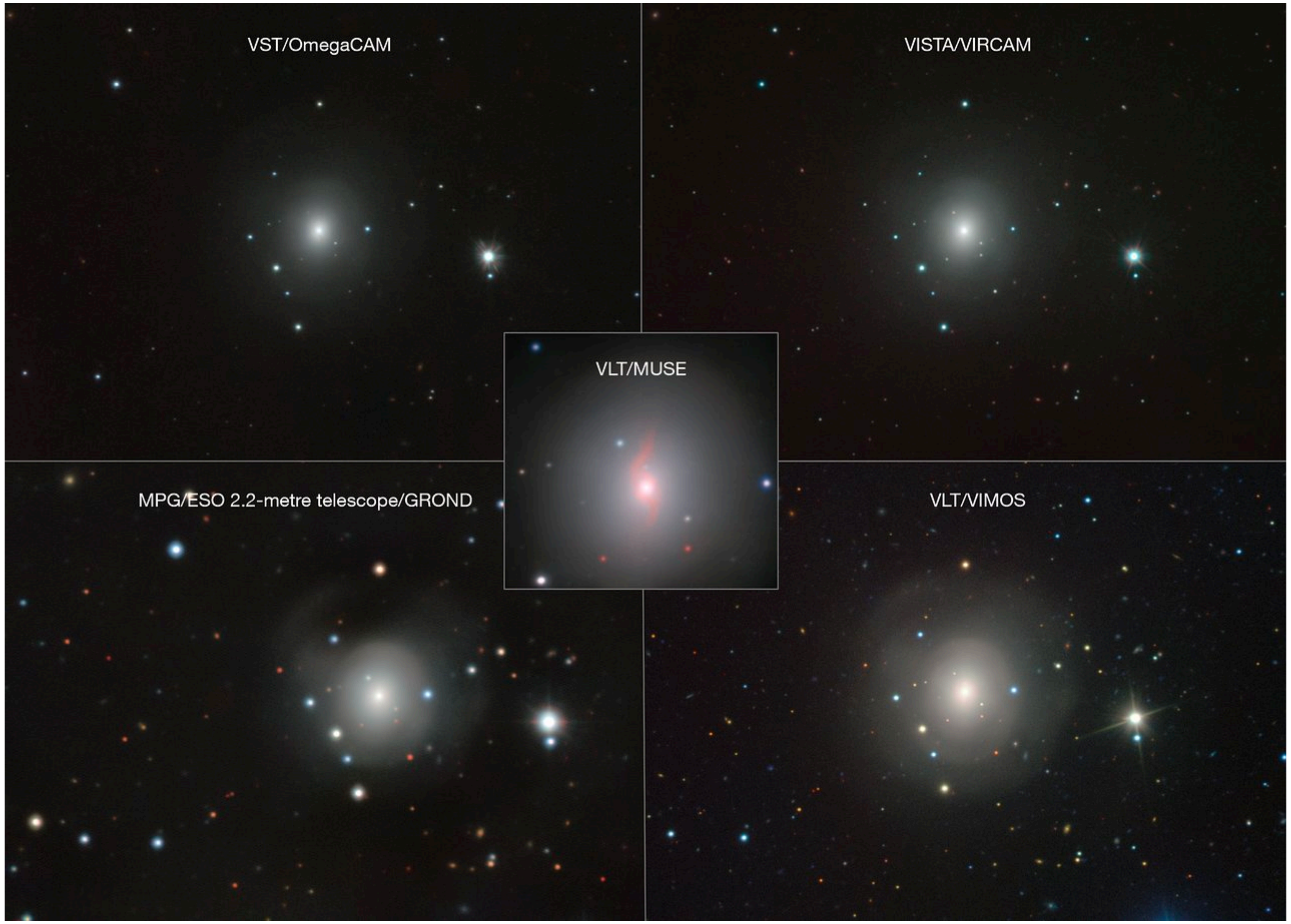


Credit: ESO/M. Kornmesser

Integral Field Spectroscopy

Example analyses

3 colour images



Credit: VLT/VIMOS. VLT/MUSE, MPG/ESO 2.2-metre telescope/GROND, VISTA/VIRCAM, VST/OmegaCAM

Integral Field Spectroscopy

Example analyses

3 colour images (and videos!)

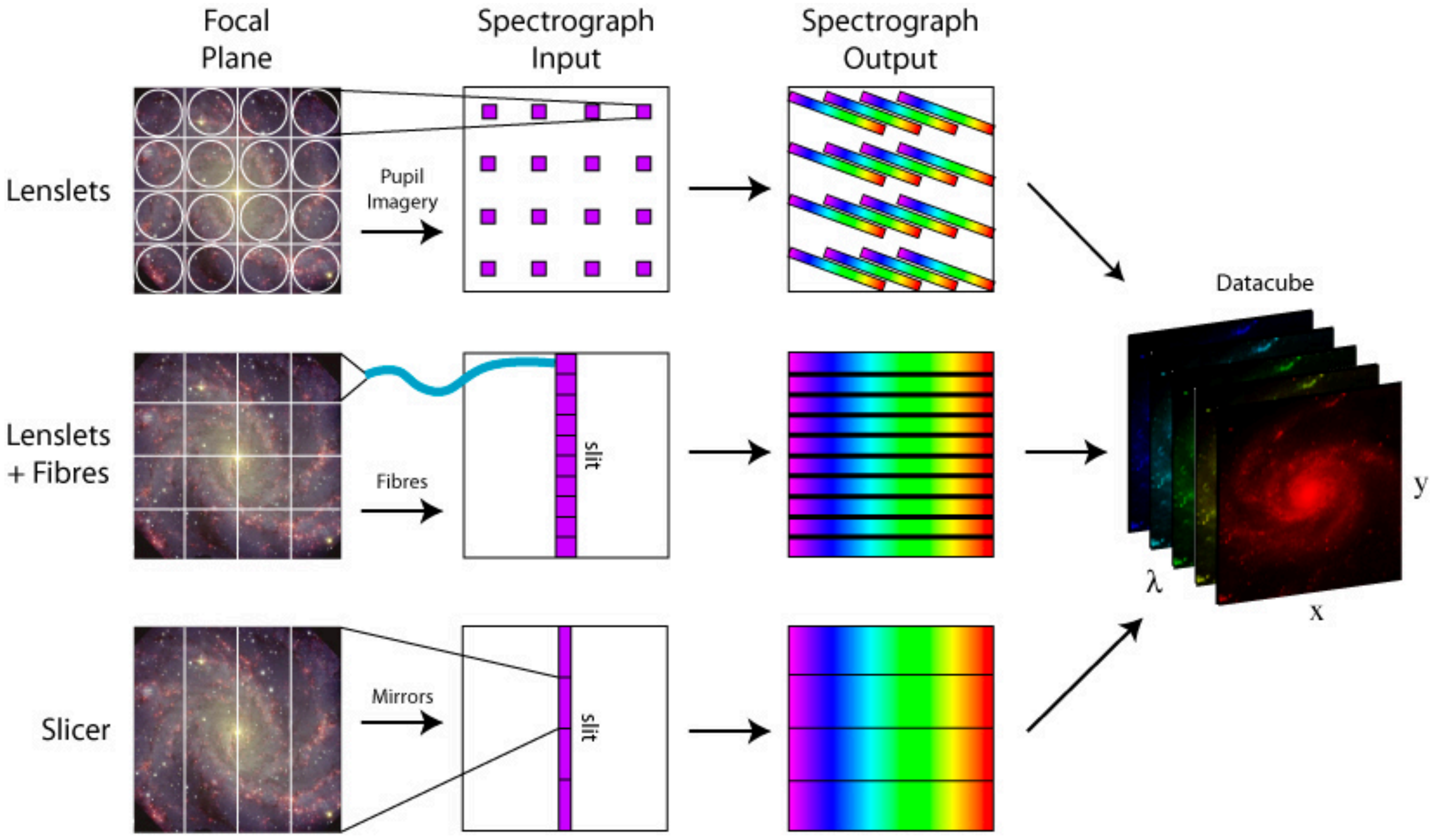
Credit: ESO/MUSE consortium/R. Bacon

MUSE

The Multi-Unit Spectroscopic Explorer

Integral Field Spectroscopy

IFS techniques

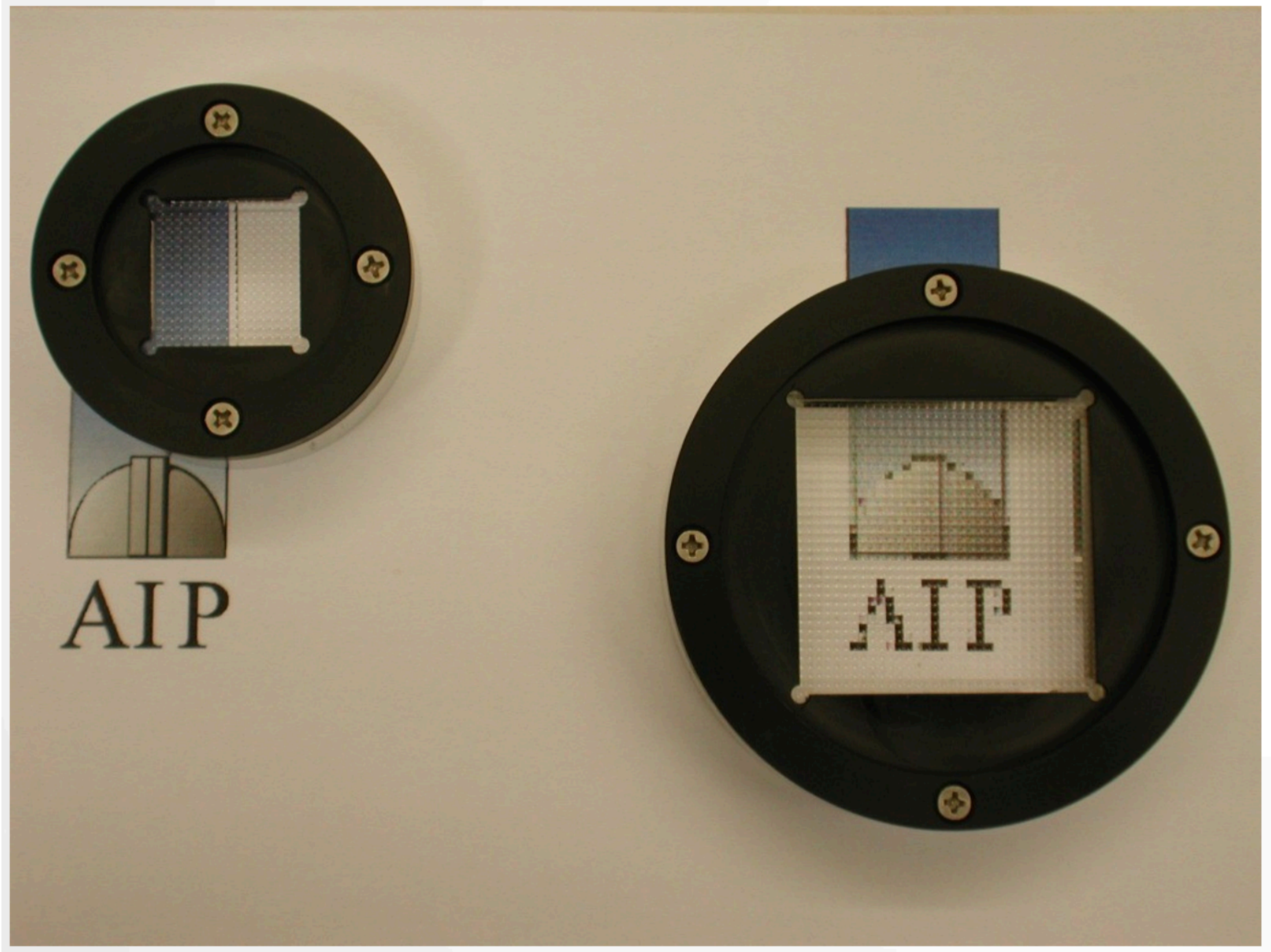


Credit: M. Westmoquette

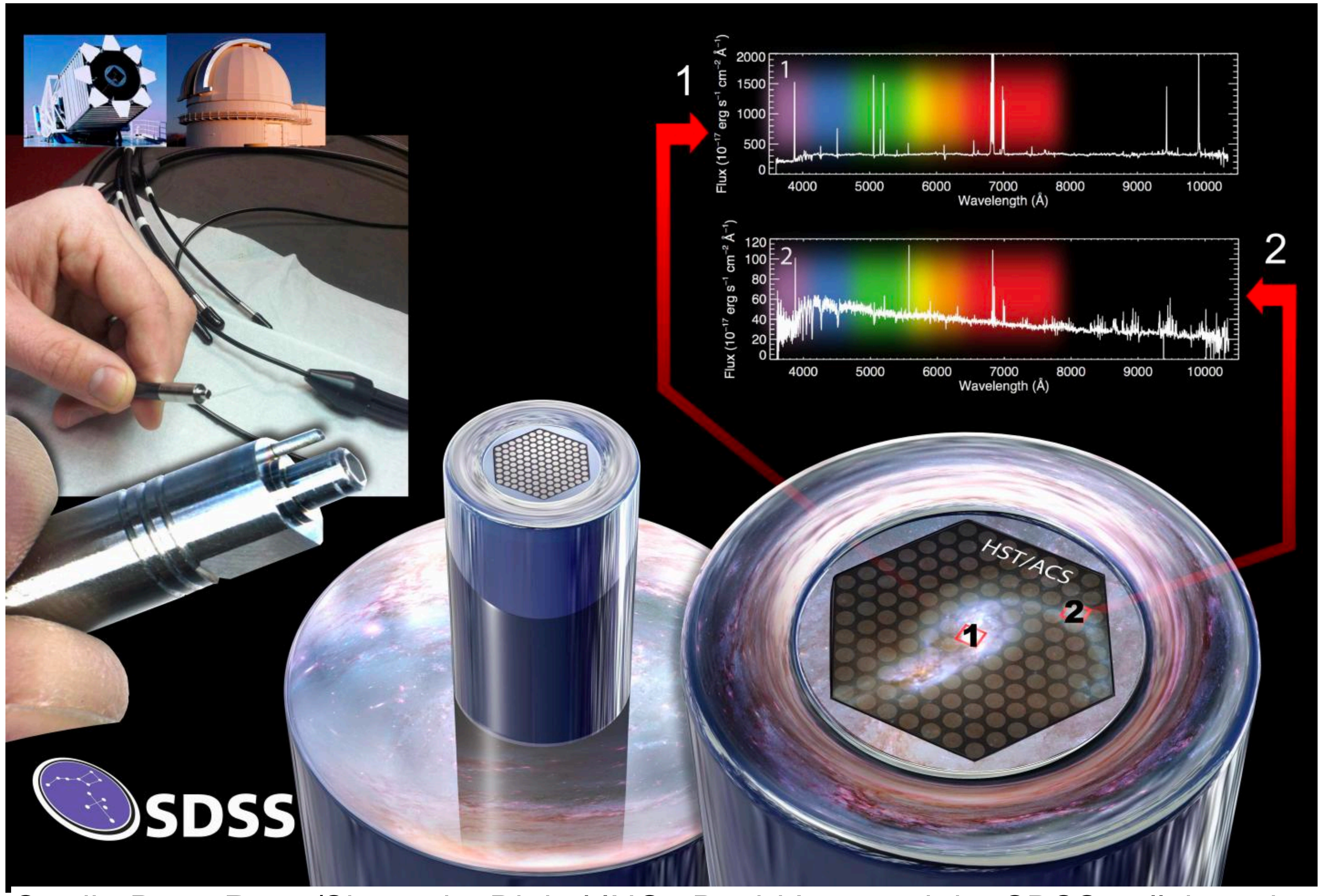
Integral Field Spectroscopy

IFS using fibers

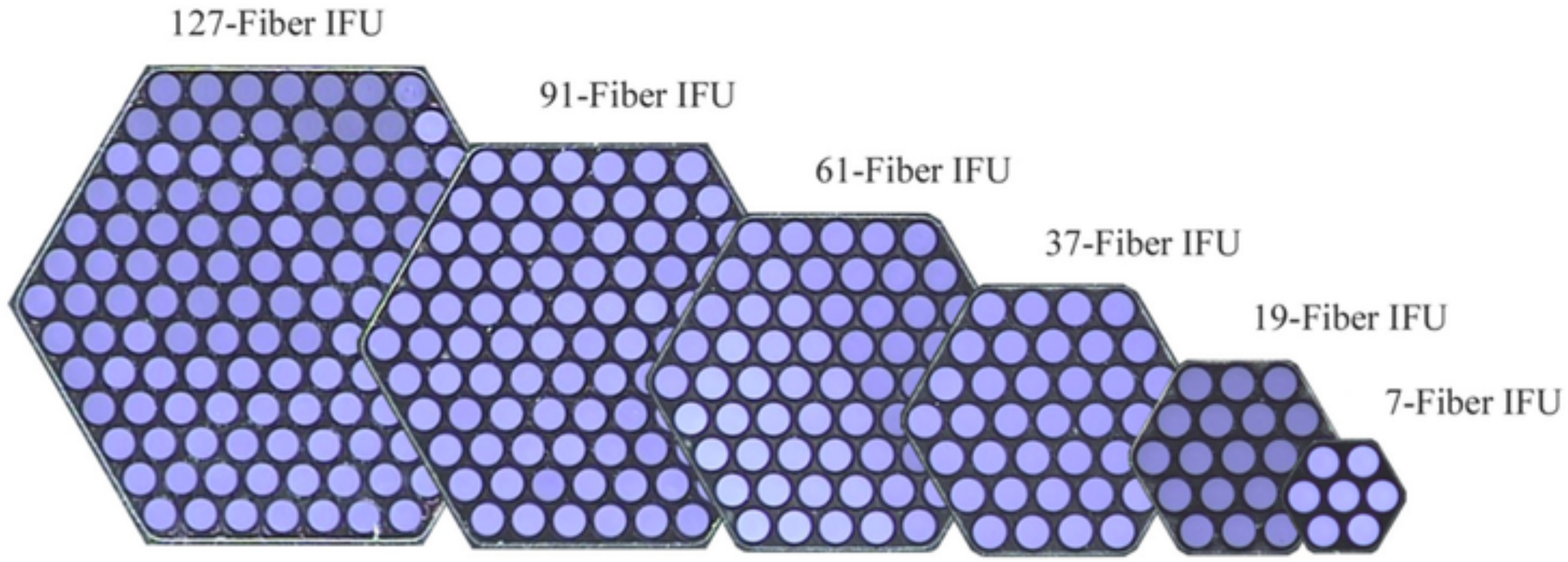
- **e.g. MaNGA**
- Fiber-bundles of different sizes
- Dither pattern requires to fill in the gaps between fibers
- Artifacts in the final cube due to converting light from circular fibers into square pixels



PMAS, credit: M. M. Roth



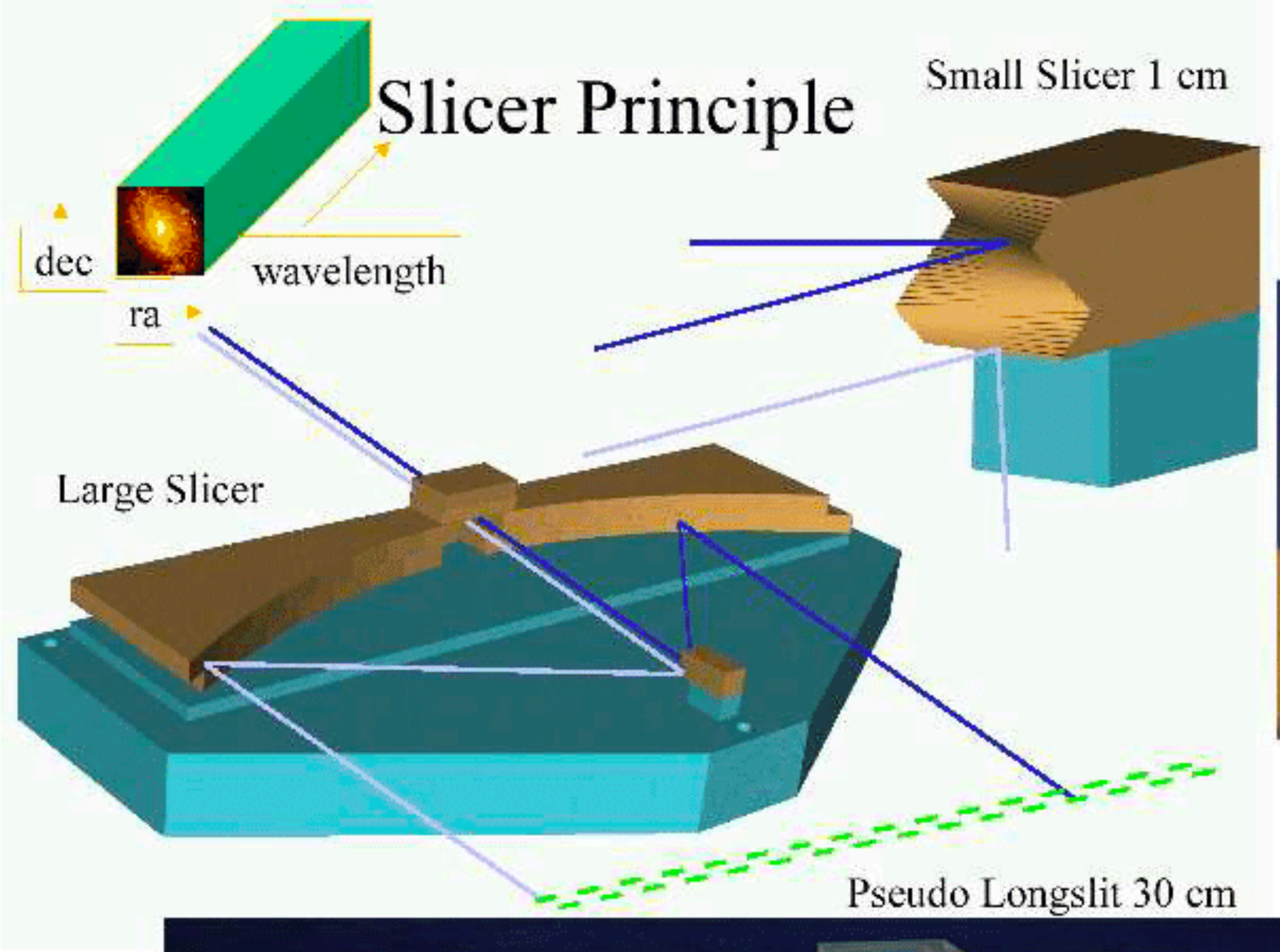
Credit: Dana Berry/Skyworks Digital INC., David Law and the SDSS collaboration

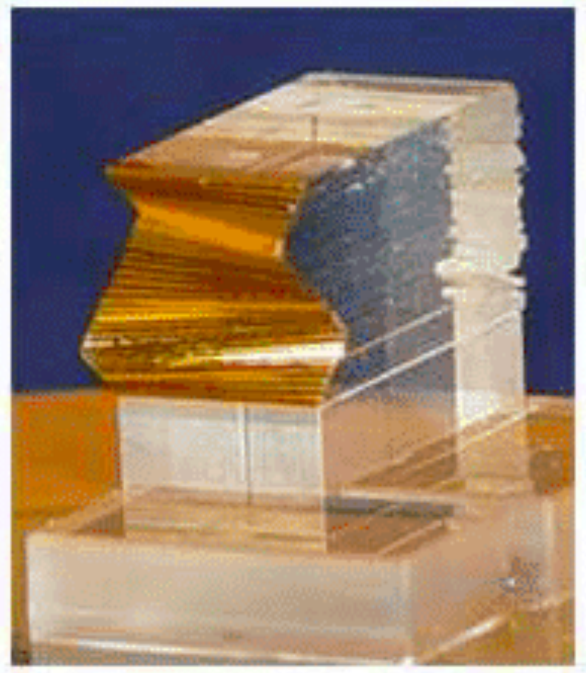


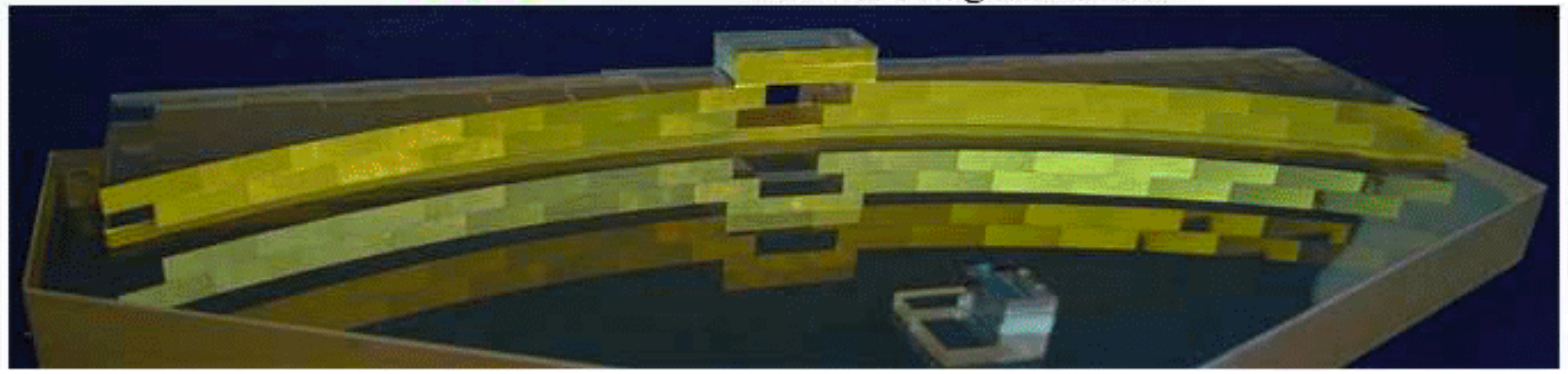
Integral Field Spectroscopy

IFS using slicers

- **e.g. SINFONI**
- Input image is split up into slit lets using an image slicer
- Oldest technique for IFU
- Most efficient use of CCD in terms of percentage coverage of FOV
- BUT, optics are challenging to manufacture.





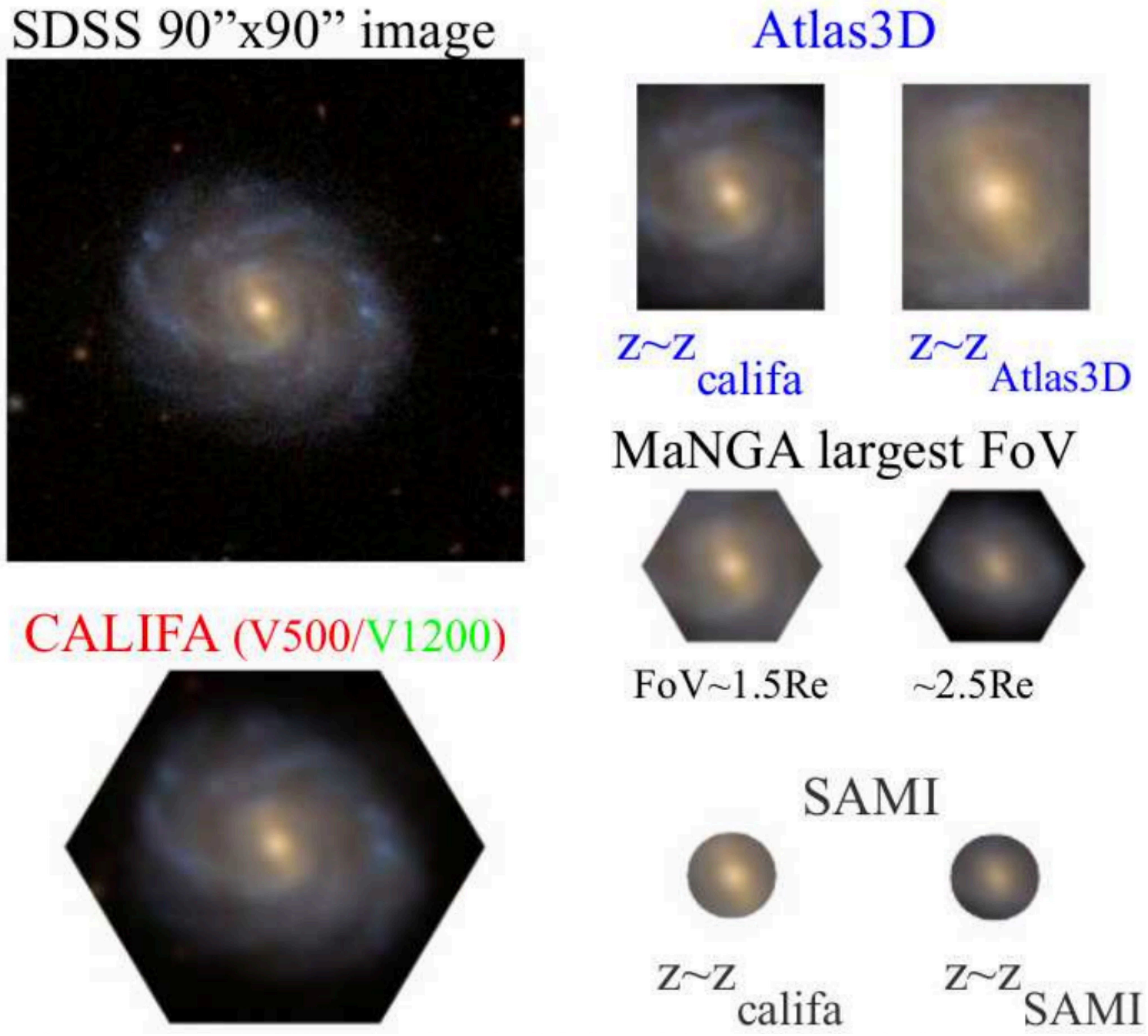


Credit: ESO

Integral Field Spectroscopy

IFS instruments/surveys currently in use

Surveys
Unless you're a member of the team, you have no say in the targets



Sanchez et al (2014)

Instrument
You can submit proposals to observe the target you are interested in

MUSE (VLT)

KCWI (Keck II)

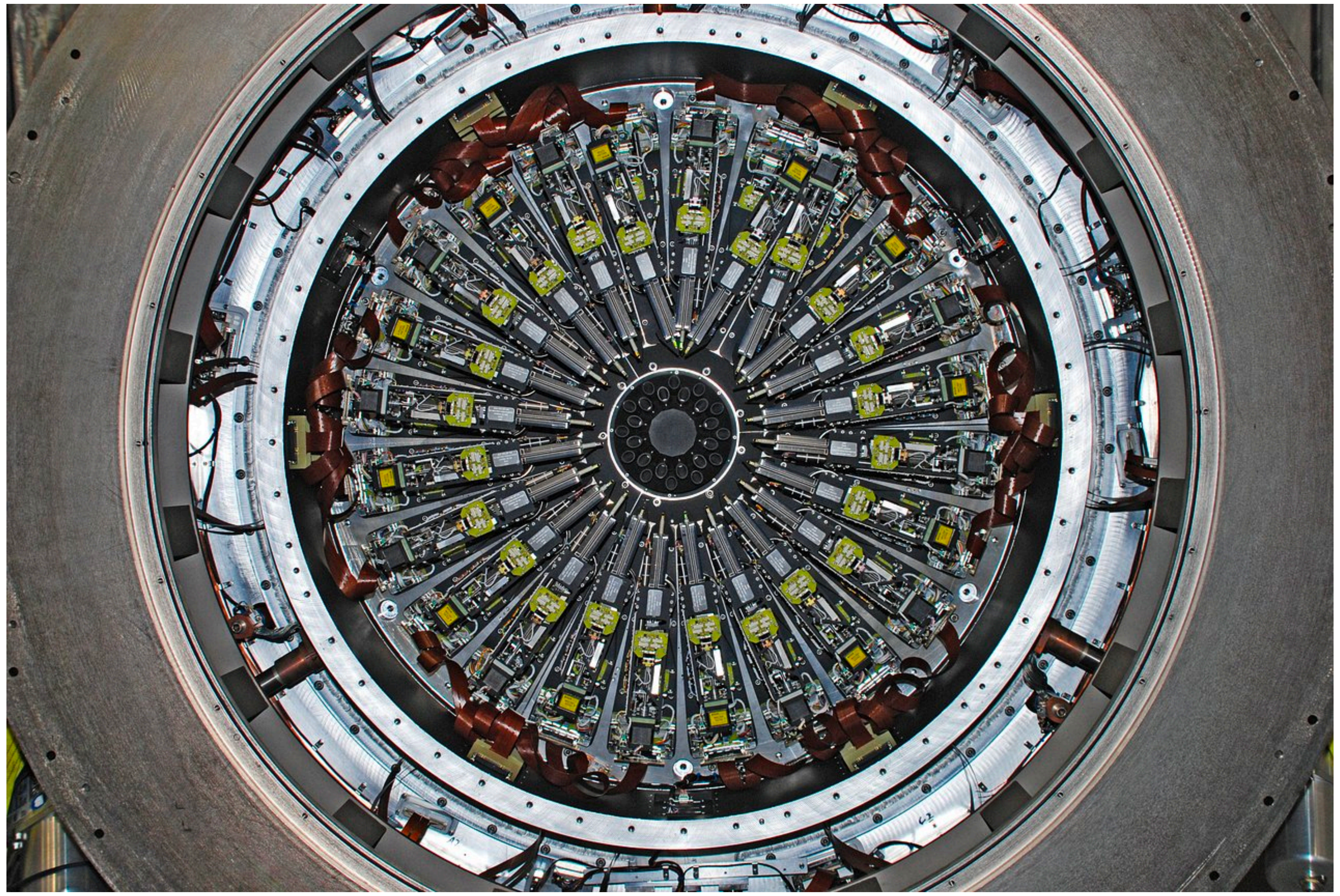
KMOS (ESO)

WEAVE (WHT)

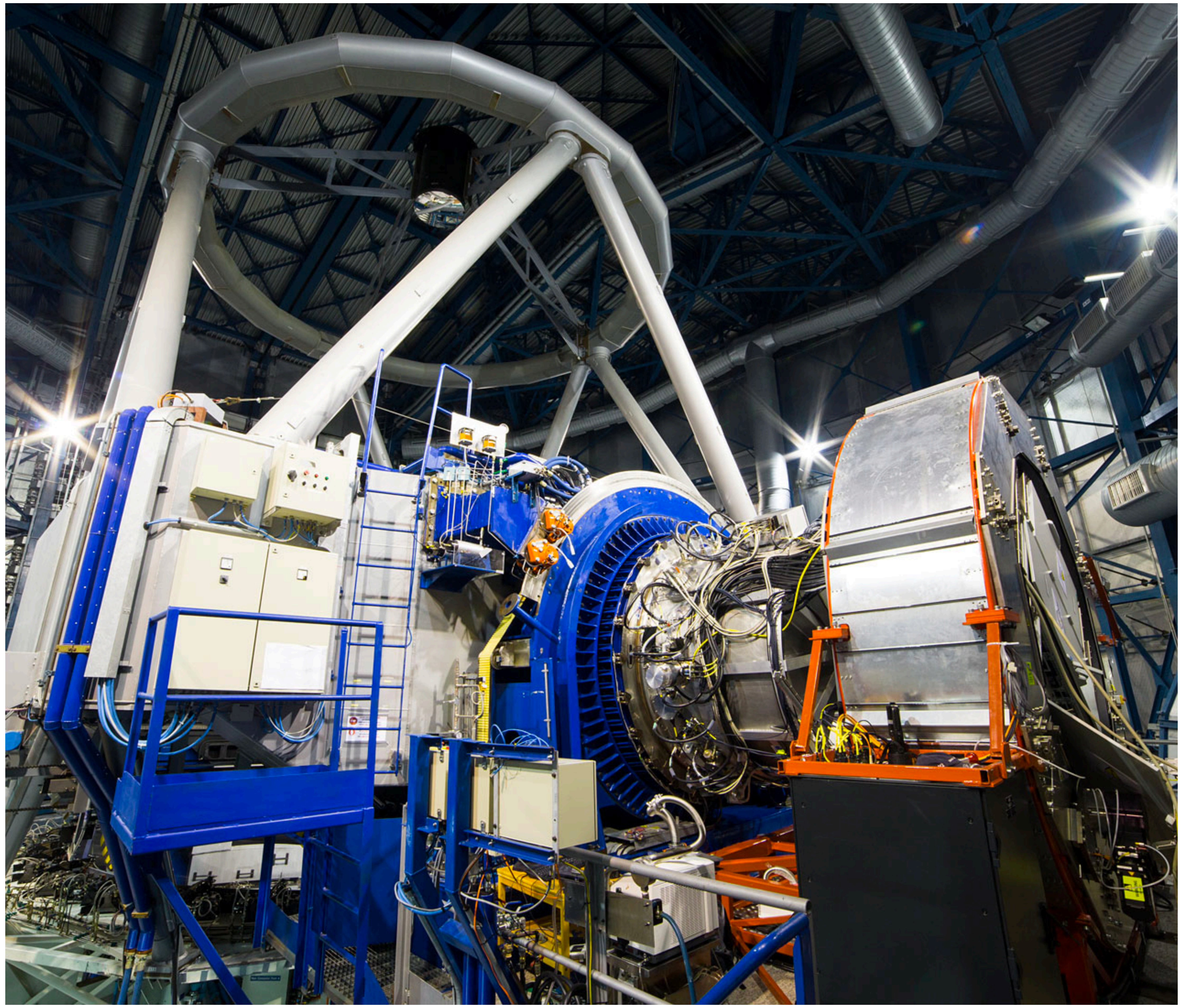
Integral Field Spectroscopy

IFS instruments/surveys currently in use

- **<u>KMOS</u>**
- 24 deployable IFUs, each with a FOV 2.8”x2.8” and spatial resolution 0.2”/pixel
- Infrared



Credit: STFC/UKATC/ESO

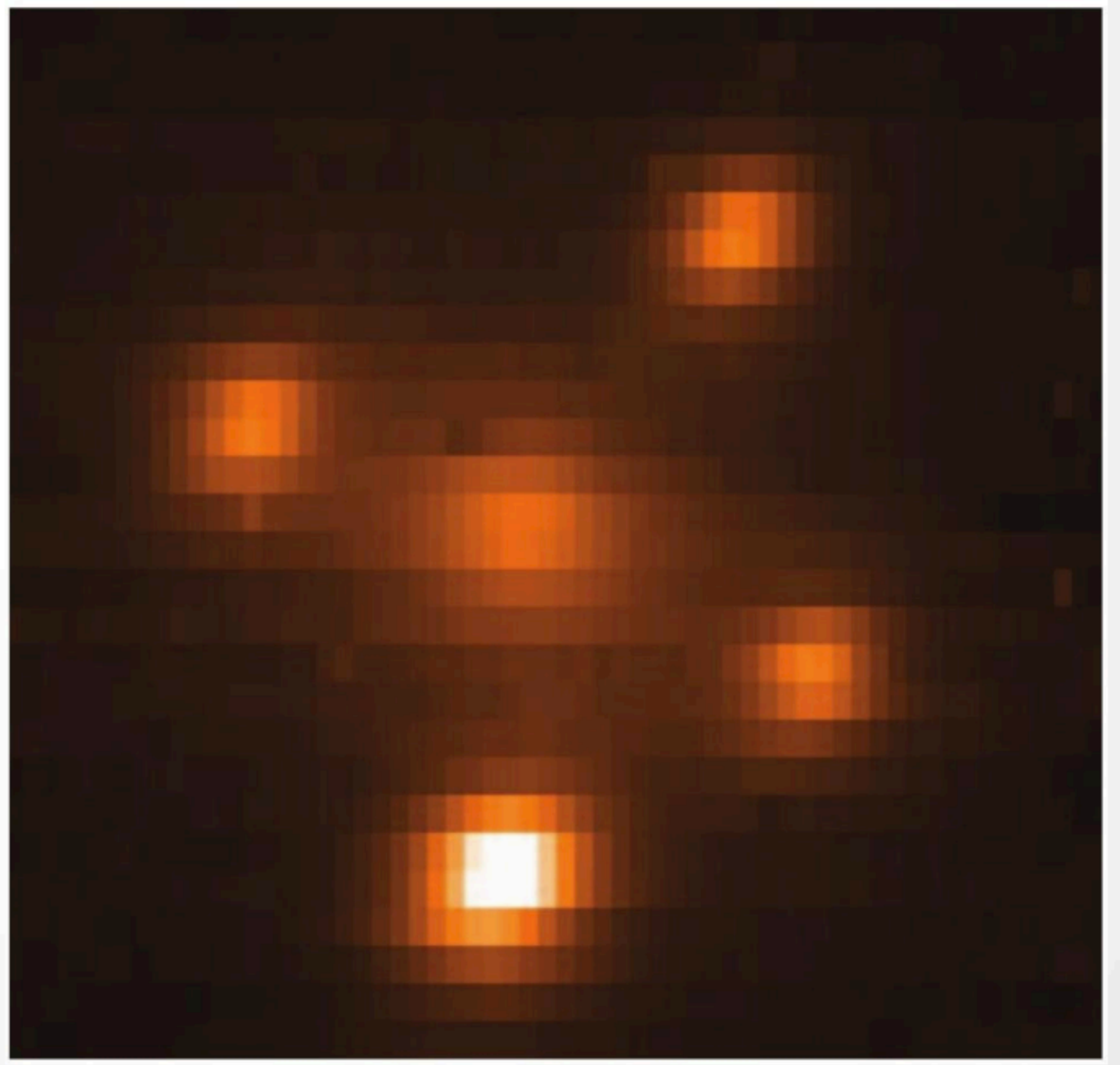


Credit: ESO/G. Lombardi

Integral Field Spectroscopy

IFS instruments/surveys currently in use

- **<u>SINFONI</u>**
- AO assisted IR IFS
- FOV from 0.8”x0.8” to 8”x8”
- One of the most successful IFS
- Recently decommissioned :-(



Einstein Cross, Bonnet et al (2004)

Credit: ESO

Integral Field Spectroscopy

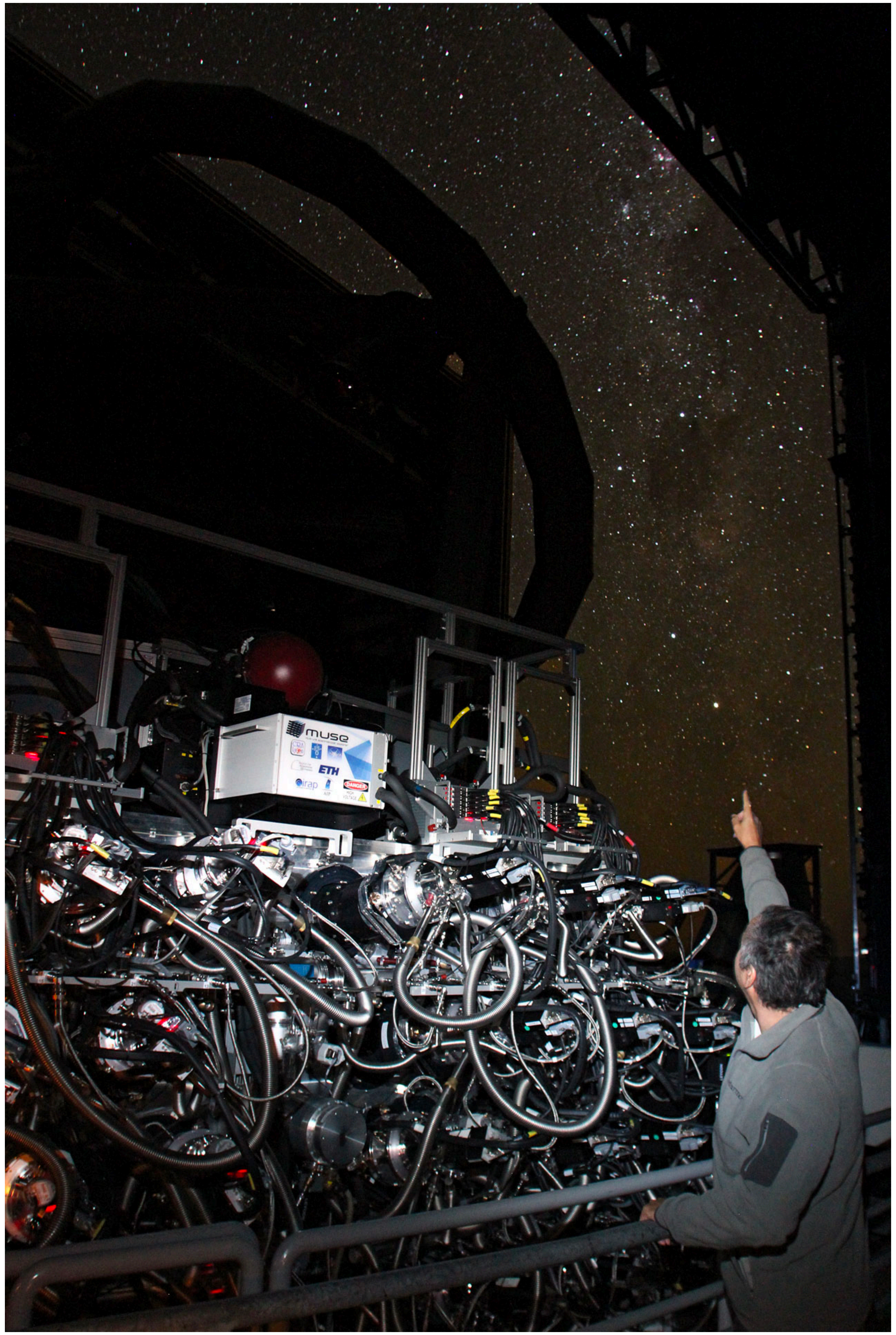
IFS instruments/surveys currently in use

- **<u>ERIS</u>**
- IR IFU and imager
- Will recycle the SINFONI detector :-)
- First light 2020

Integral Field Spectroscopy

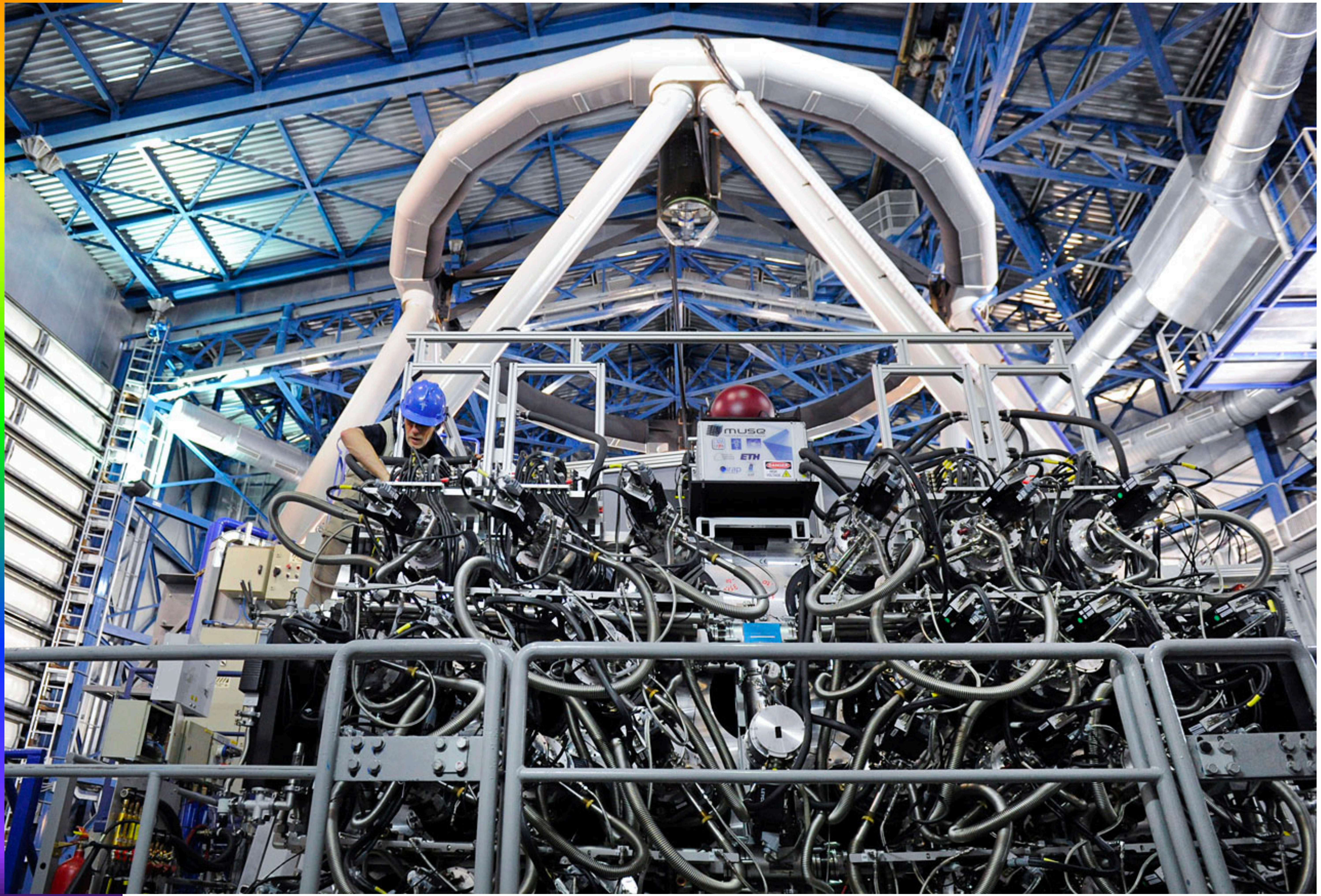
IFS instruments/surveys currently in use

- **<u>MUSE</u>**
- Optical IFU with widest FOV currently in operation
- FOV 1’x1’ (WFM)
- Spaxel size 0.2”/pixel (WFM)
- Spectral resolution 2000-4000
- In operation since 2014



Credit: ESO/Ghaouti Hansali/Fernando Selman

MUSE: Multi-Unit Spectroscopic Explorer



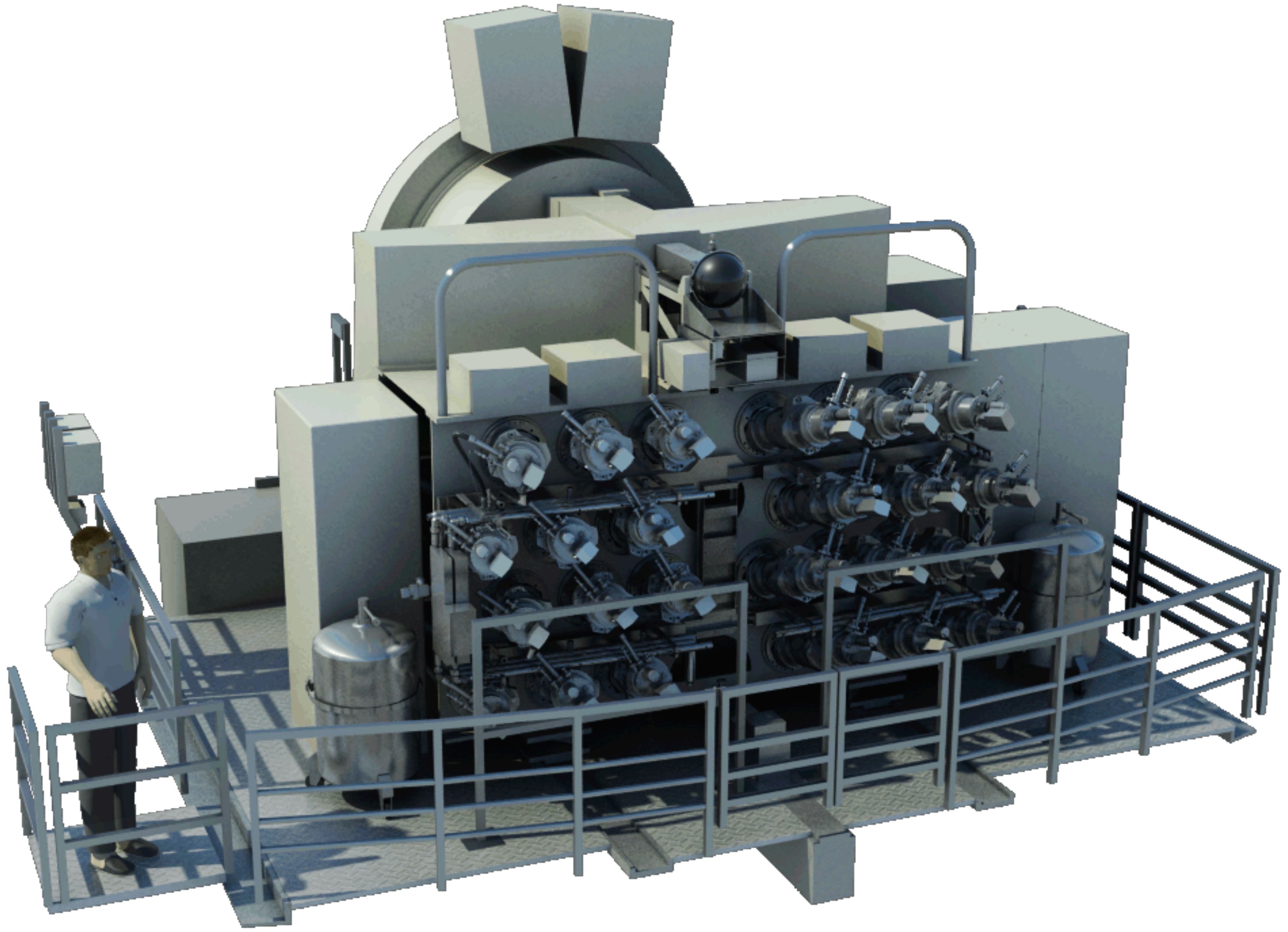
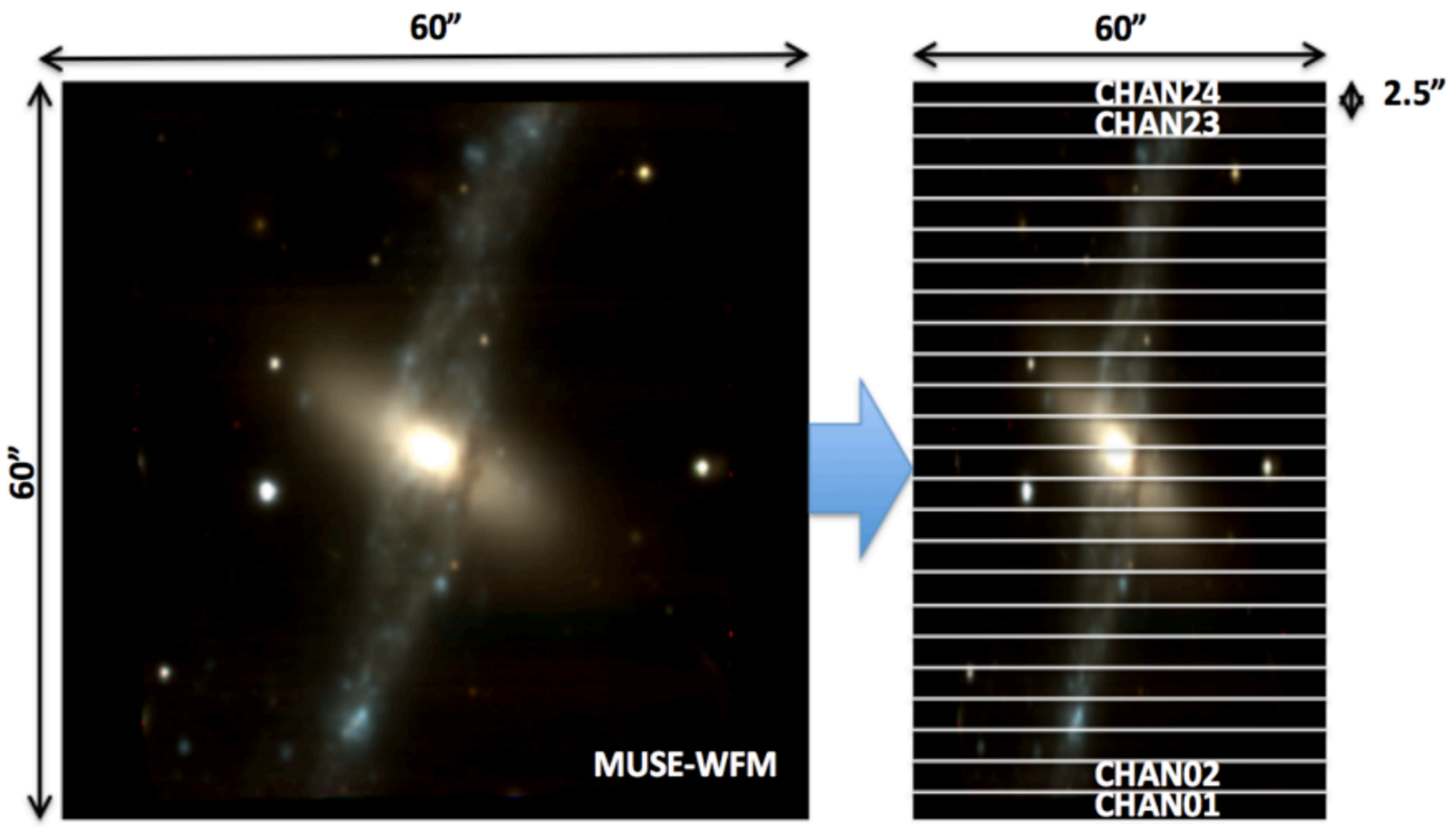


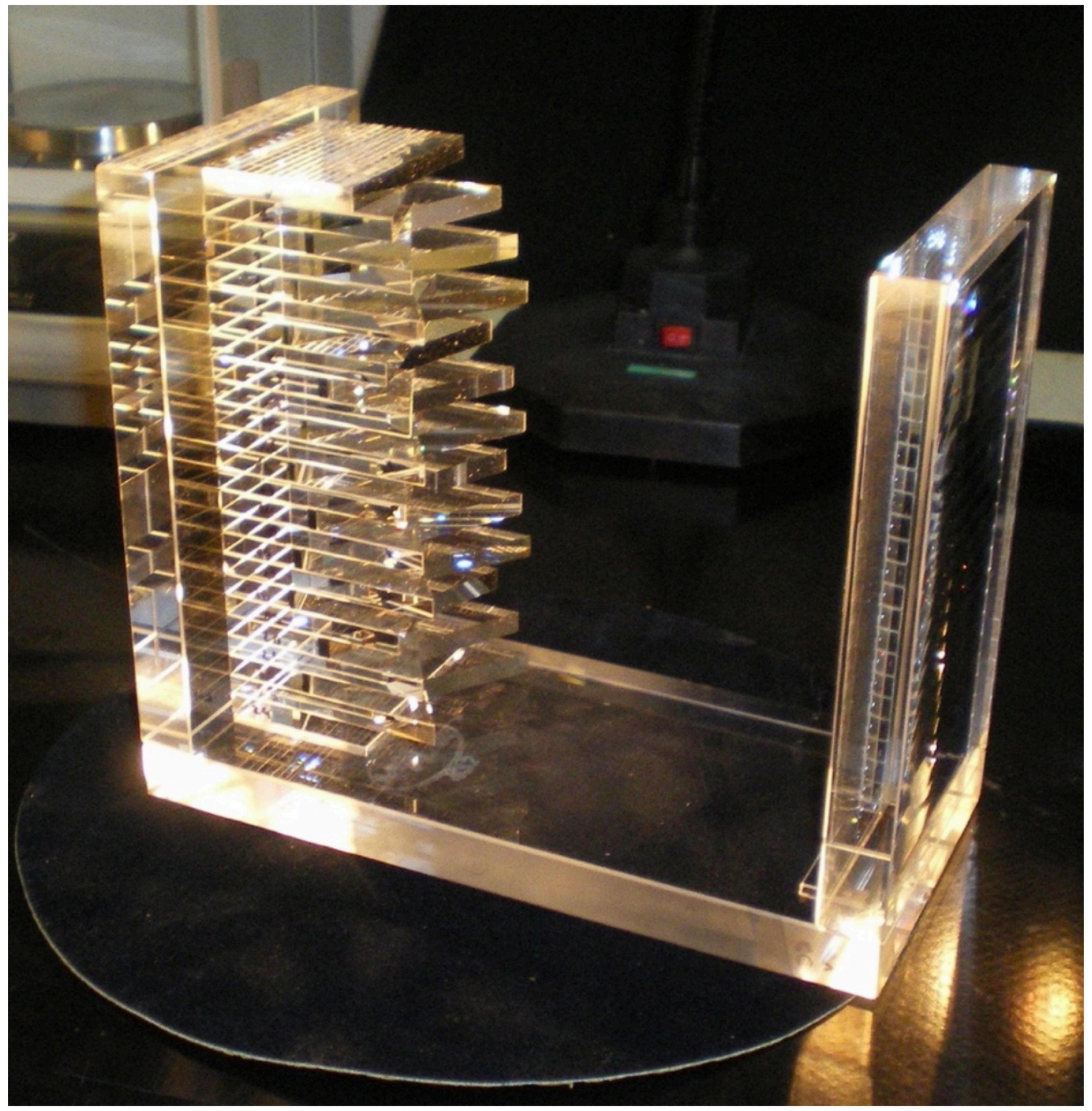
Image credit: ESO

MUSE: Multi-Unit Spectroscopic Explorer

Integral Field or 3D spectroscopy

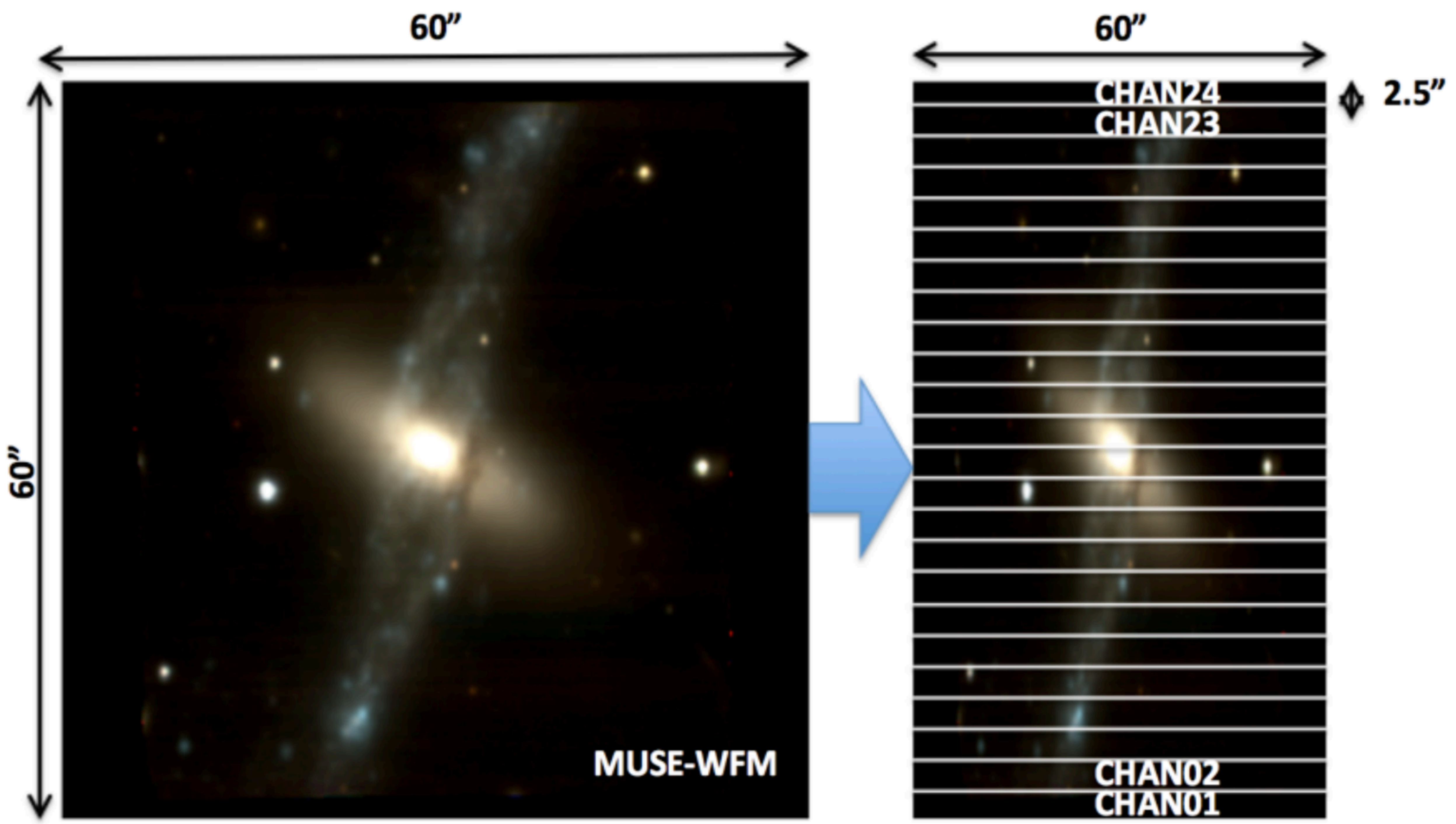


Beam Splitter
Splits up the image into 24 segments

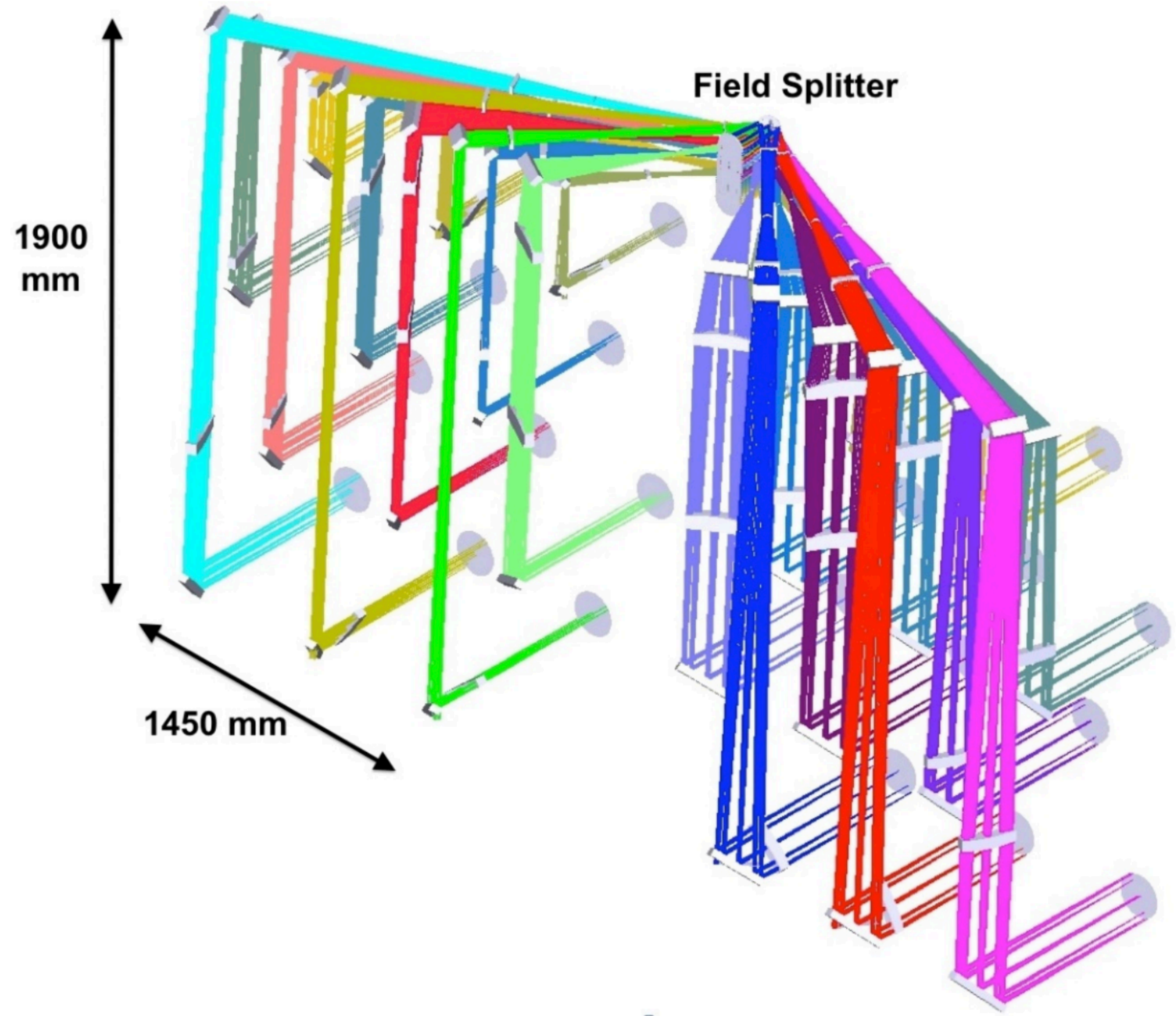


MUSE: Multi-Unit Spectroscopic Explorer

Integral Field or 3D spectroscopy

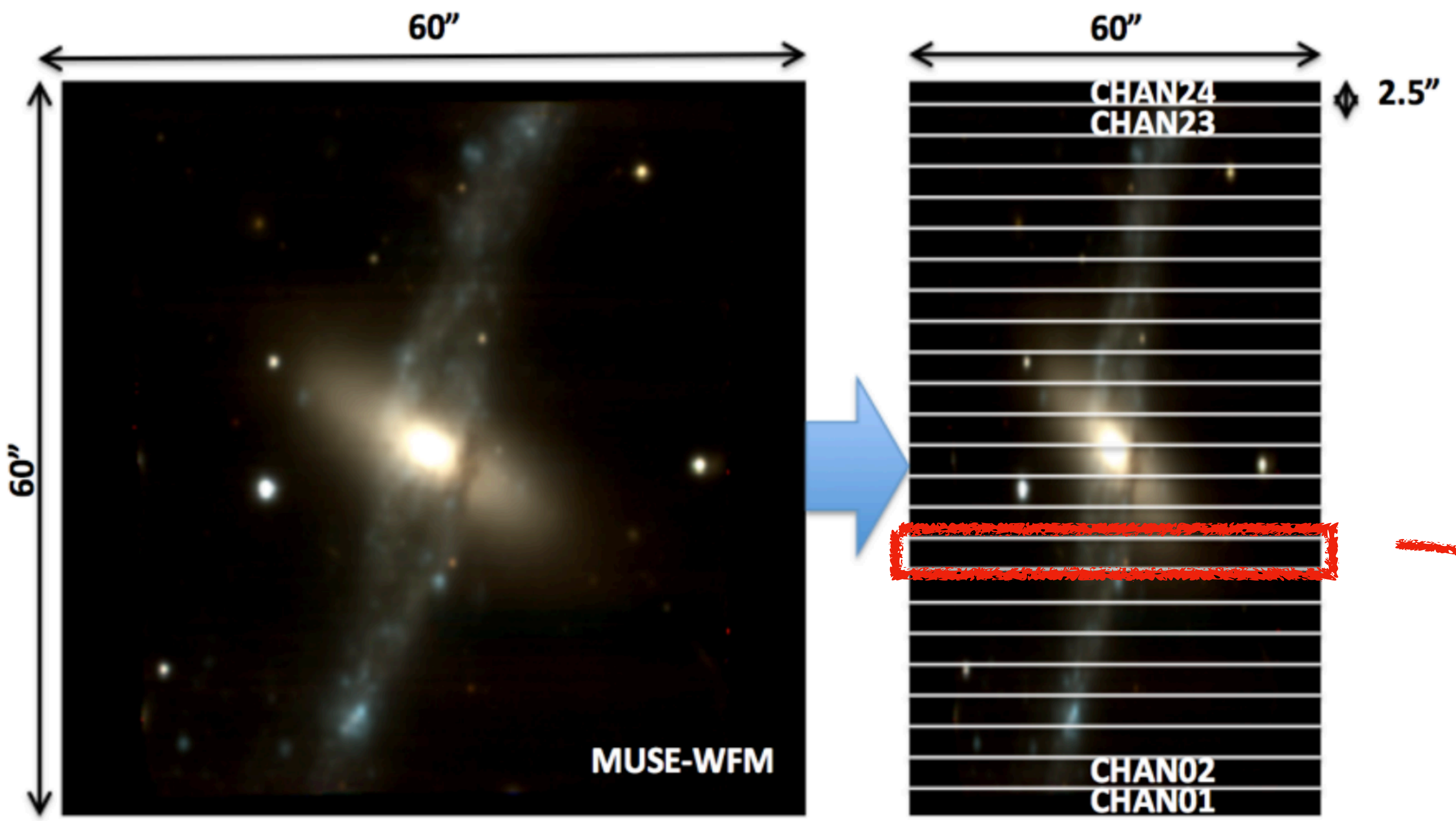


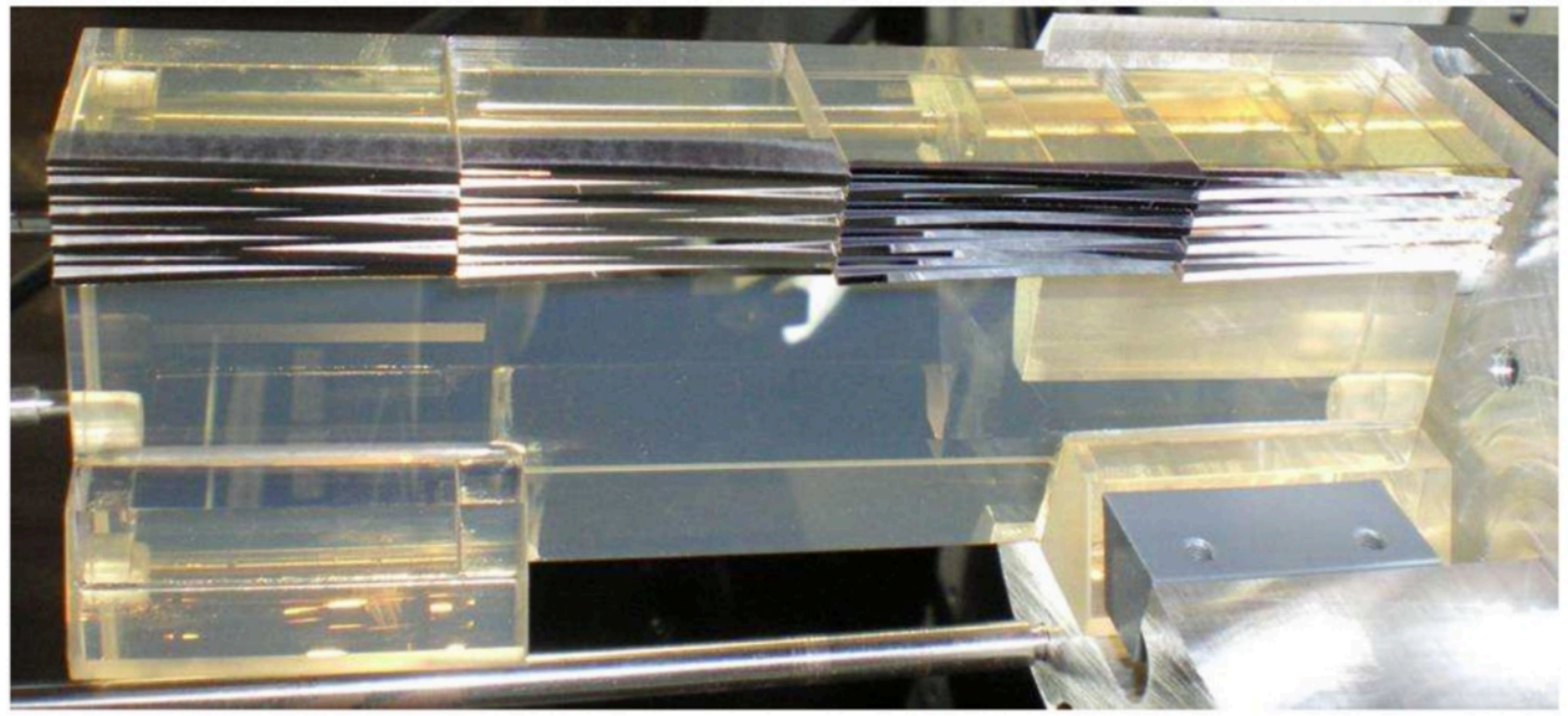
Each segmented image is directed to a separate IFU spectrograph



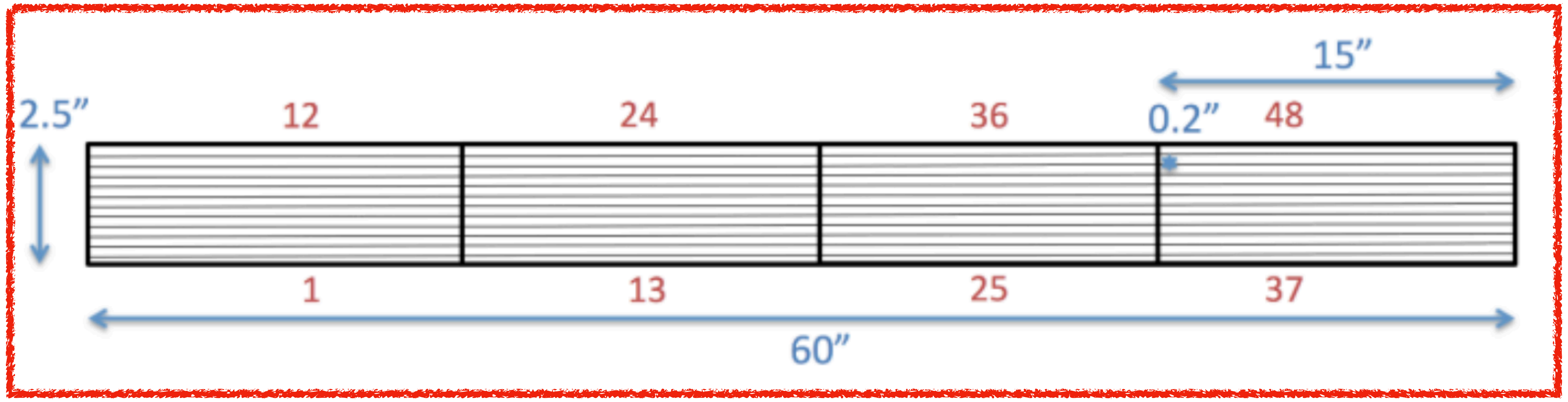
MUSE: Multi-Unit Spectroscopic Explorer

Integral Field or 3D spectroscopy





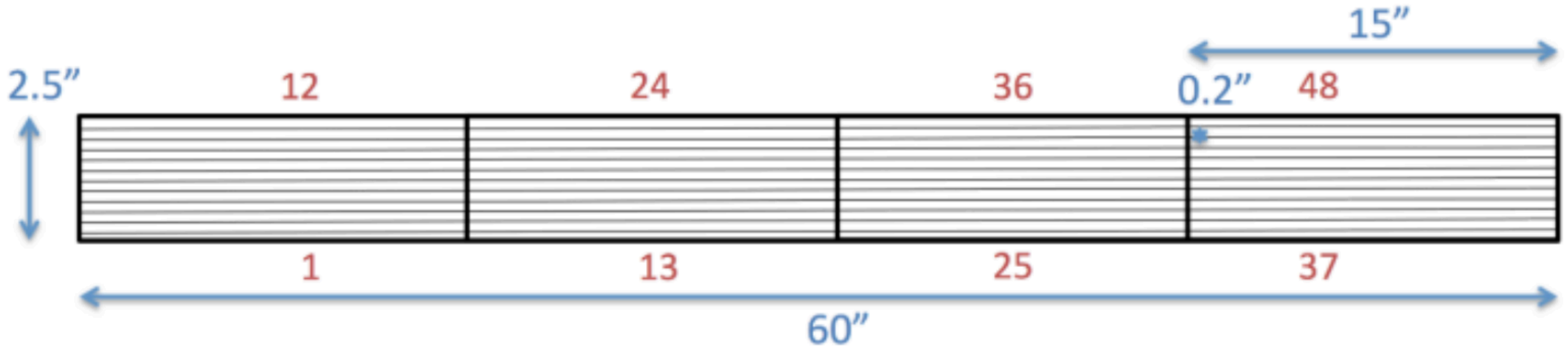
Within the IFU spectrograph, the image is further split up into 48 slitlets.



Within the spectrograph, the image is split up again into a further 48 slitlets

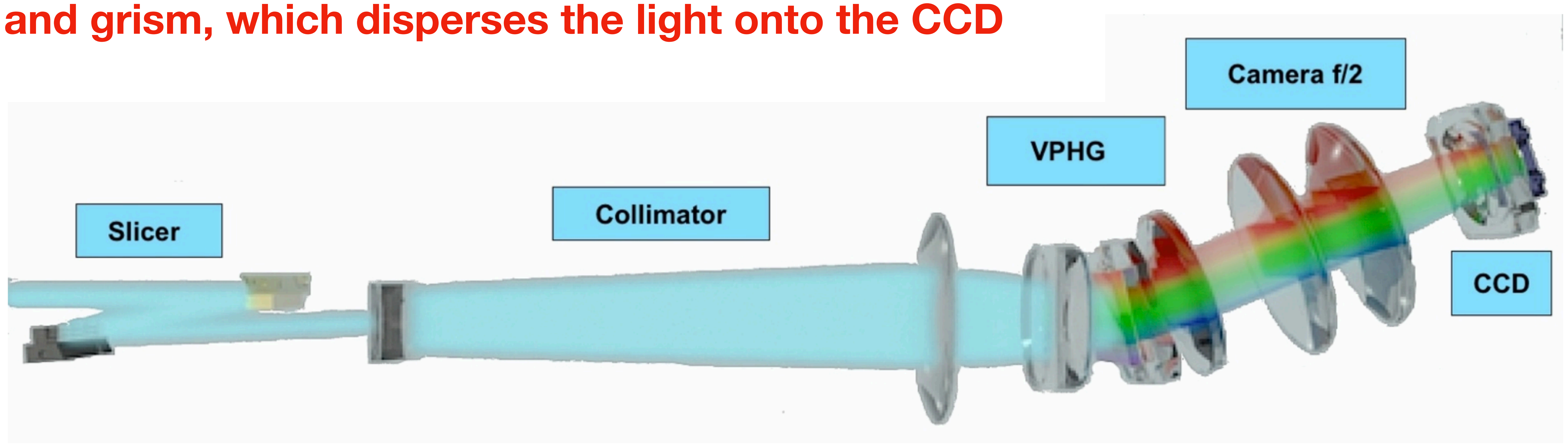
MUSE: Multi-Unit Spectroscopic Explorer

Integral Field or 3D spectroscopy



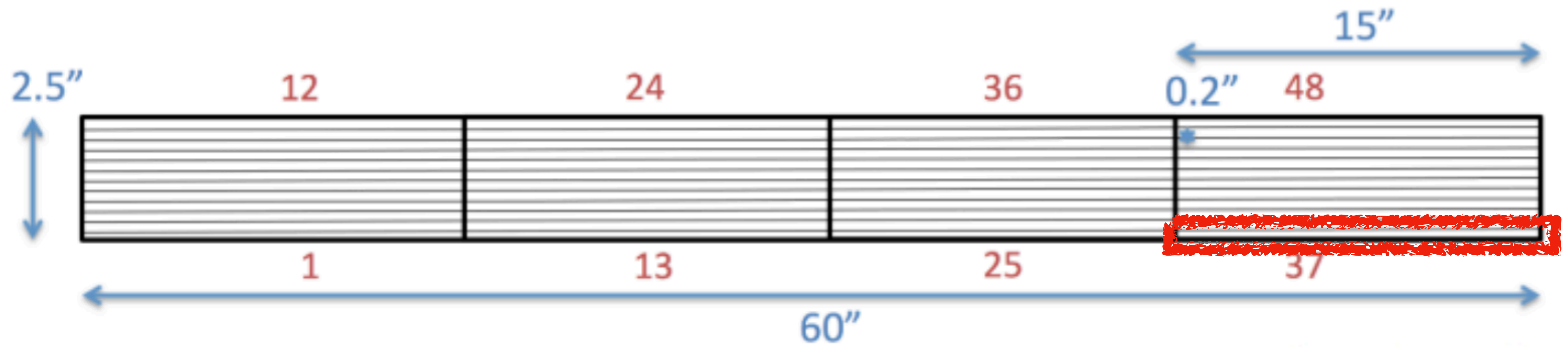
Within the spectrograph, the image is split up again into a further 48 slitlets

The light from each slitlet passes through a collimator and grism, which disperses the light onto the CCD



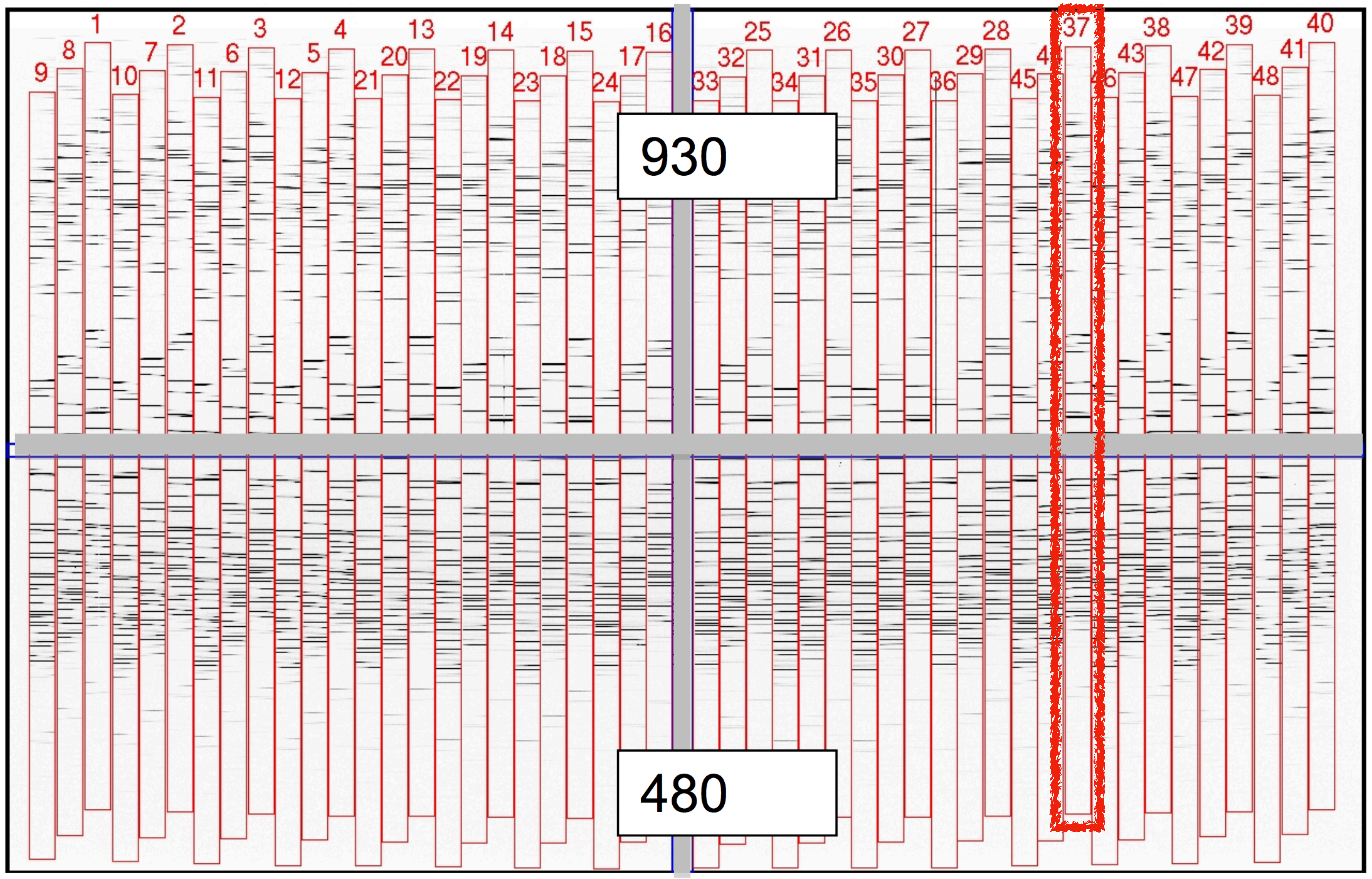
MUSE: Multi-Unit Spectroscopic Explorer

Integral Field or 3D spectroscopy



Within the spectrograph, the image is split up again into a further 48 slitlets

Each slitlet corresponds to a spectrum on the CCD



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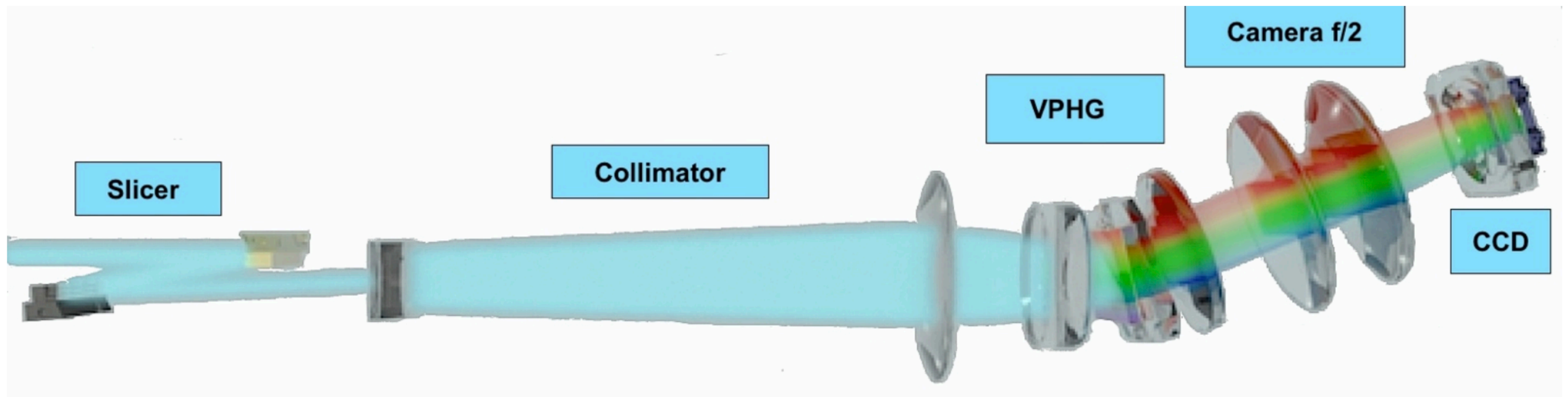
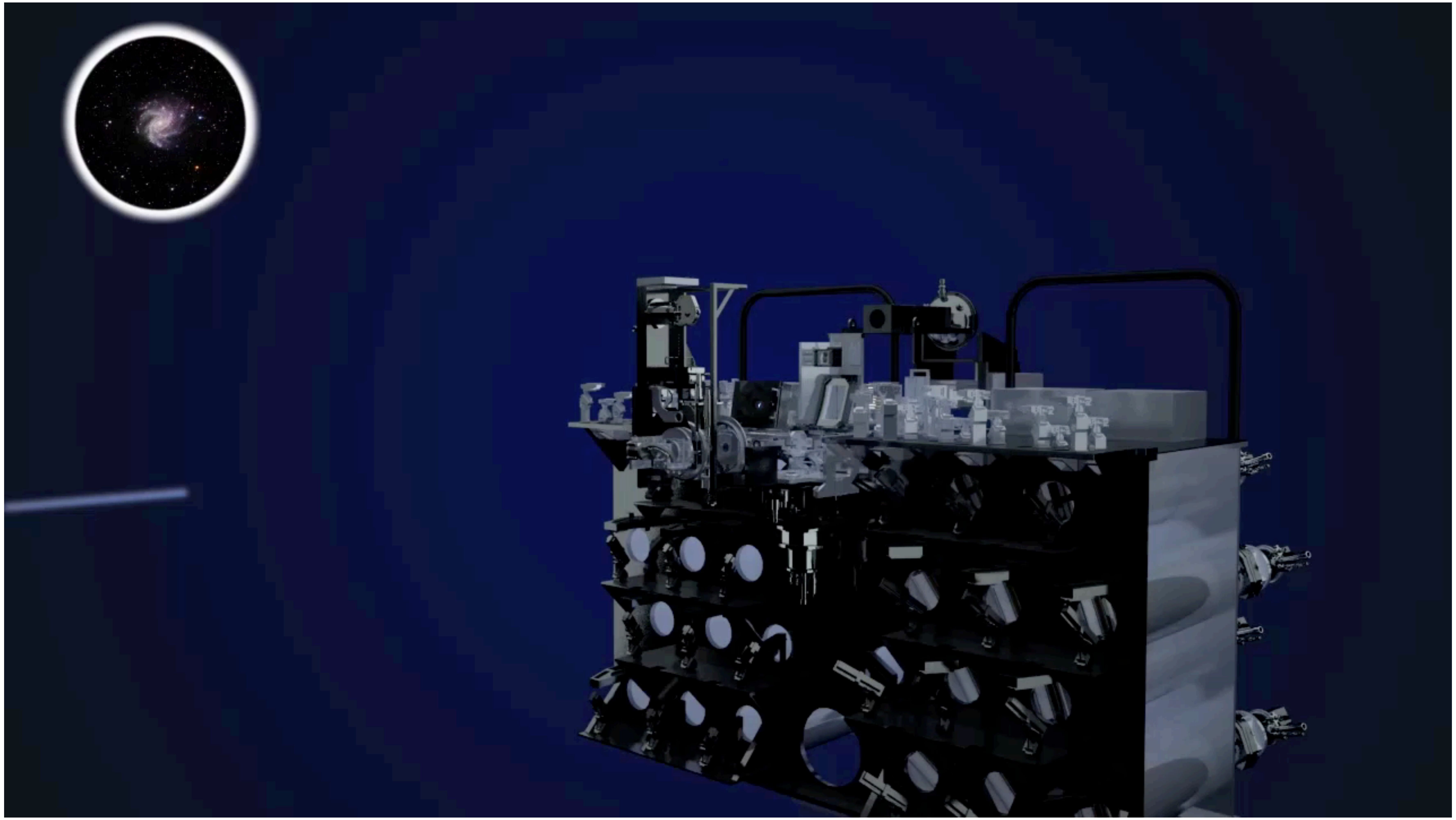


MUSE: Multi-Unit Spectroscopic Explorer

A Journey Through MUSE



credit: Univ. de Lyon,
Video URL: http://muse.univ-lyon1.fr/IMG/mp4/Decoupeur_Slicer.mp4

MUSE: Multi-Unit Spectroscopic Explorer

Modes

MUSE instrument mode	Spatial setting	Filter name	Spectral range (nm)
WFM-NOAO-N	WFM	Blue	480-930
WFM-NOAO-E	WFM	Clear	465-930(*) with 2nd order contamination at 850-930 nm
WFM-AO-N	WFM	Blue-Na	480-582, 597-930
WFM-AO-E	WFM	Na	465-576, 601-930(*)
NFM-AO-N	NFM	Blue-IR	480-578, 605-930 Nota: the Na Notch filter is located in GALACSI

MUSE: Multi-Unit Spectroscopic Explorer

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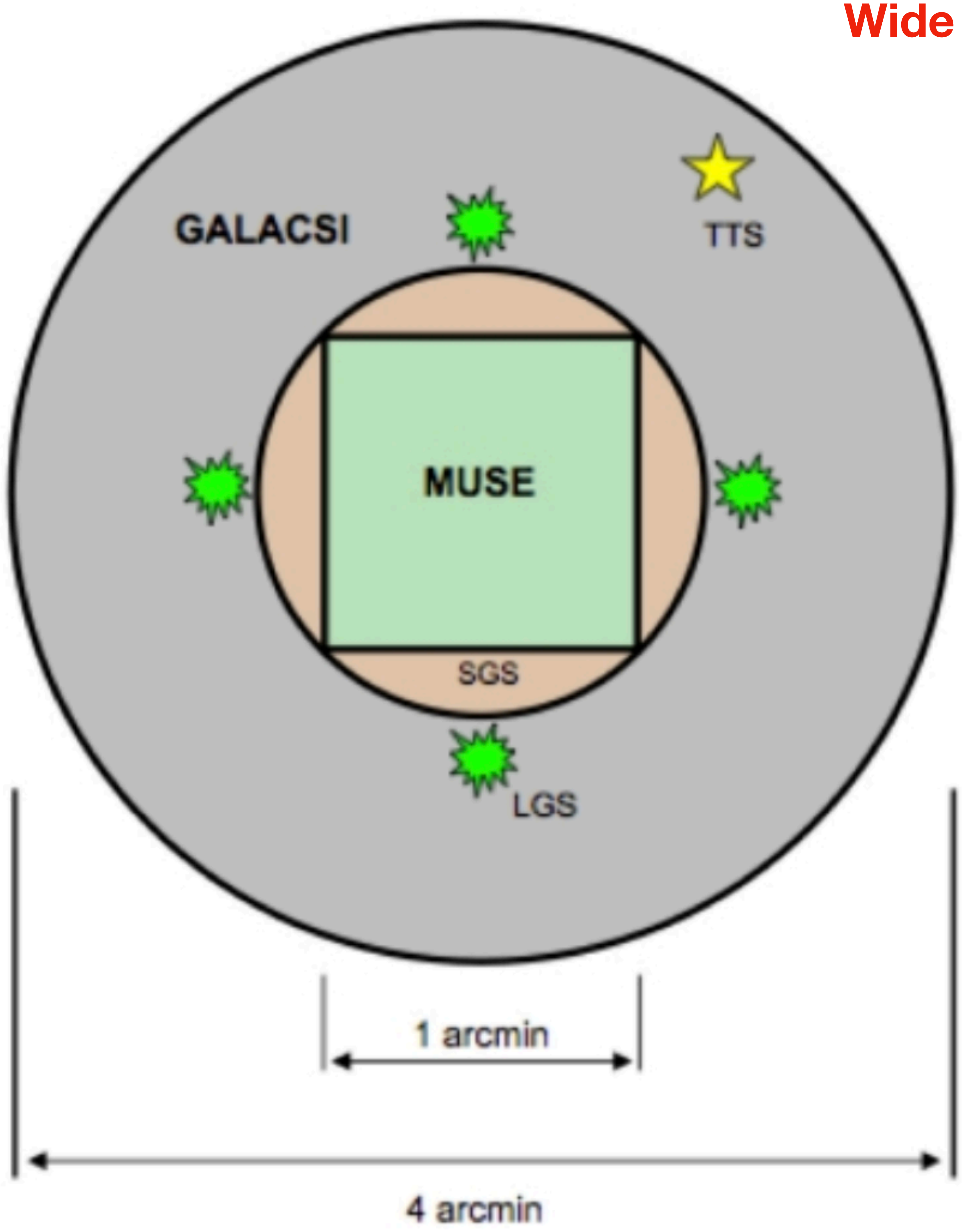
Wide/Narrow Field Mode (WFM/NFM)

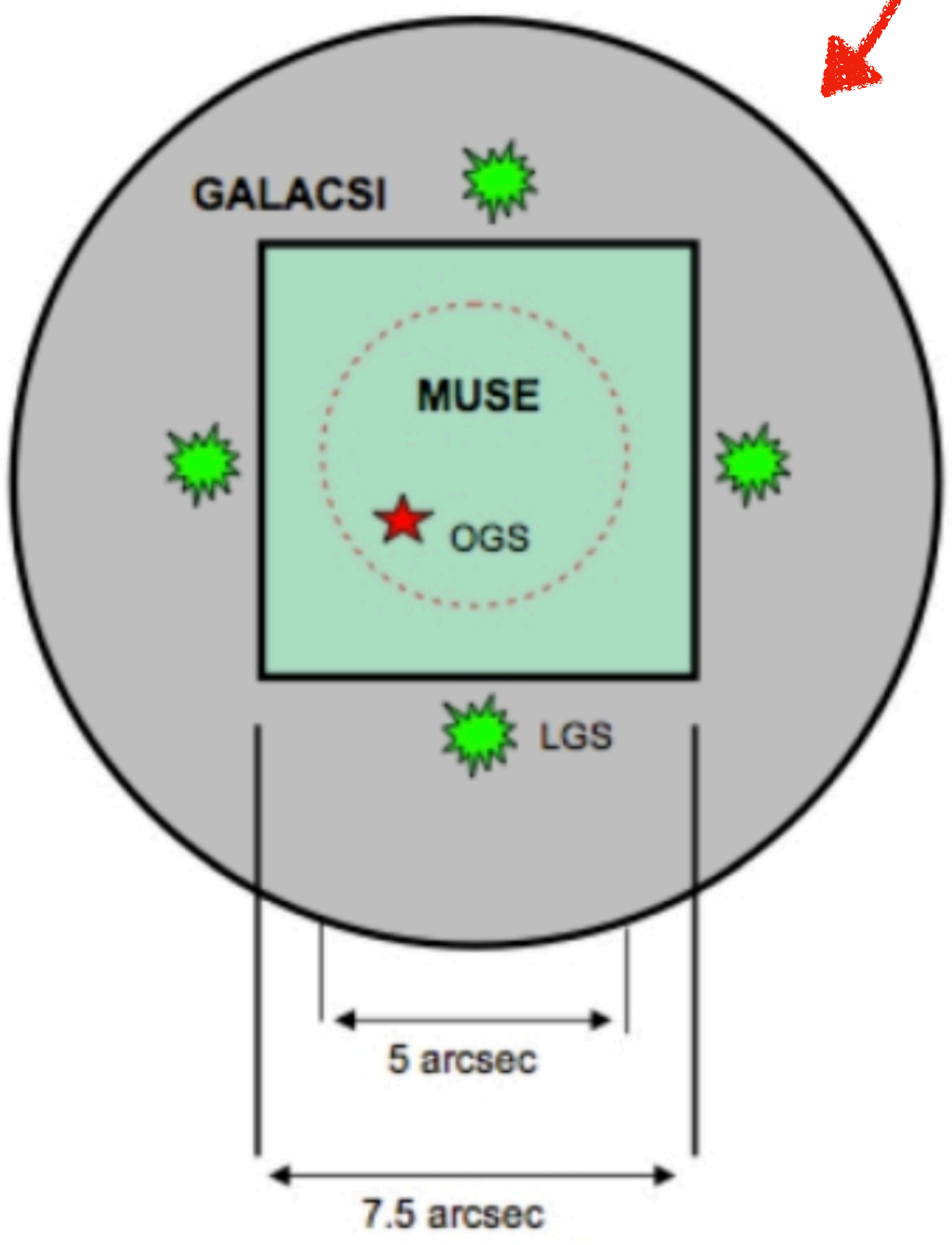
MUSE: Multi-Unit Spectroscopic Explorer

Wide Field Mode and Narrow Field Mode

Wide Field Mode (WFM)



Narrow Field Mode (NFM)



MUSE: Multi-Unit Spectroscopic Explorer

Modes

With or without adaptive optics (AO/NOAO)

MUSE instrument mode	Spatial setting	Filter name	Spectral range (nm)
WFM-NOAO-N	WFM	Blue	480-930
WFM-NOAO-E	WFM	Clear	465-930(*) with 2nd order contamination at 850-930 nm
WFM-AO-N	WFM	Blue-Na	480-582, 597-930
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NFM-AO-N	NFM	Blue-IR	480-578, 605-930 Nota: the Na Notch filter is located in GALACSI

MUSE: Multi-Unit Spectroscopic Explorer

AO and NOAO

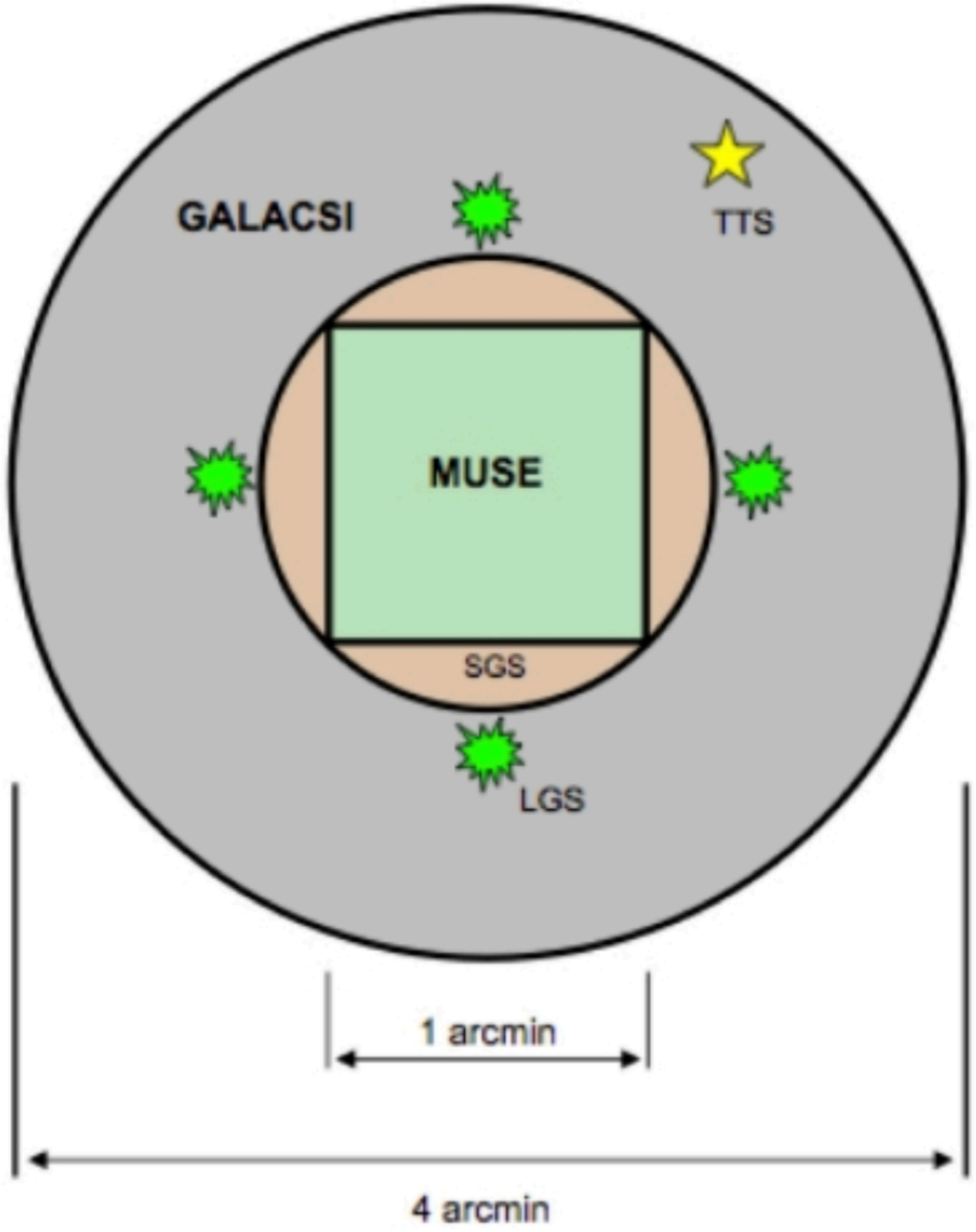

Image credit: Roland Bacon

MUSE: Multi-Unit Spectroscopic Explorer

AO and NOAO

Image credit: ESO/P. Weilbacher (AIP)

MUSE: Multi-Unit Spectroscopic Explorer

Modes

MUSE instrument mode	Spatial setting	Filter name	Spectral range (nm)
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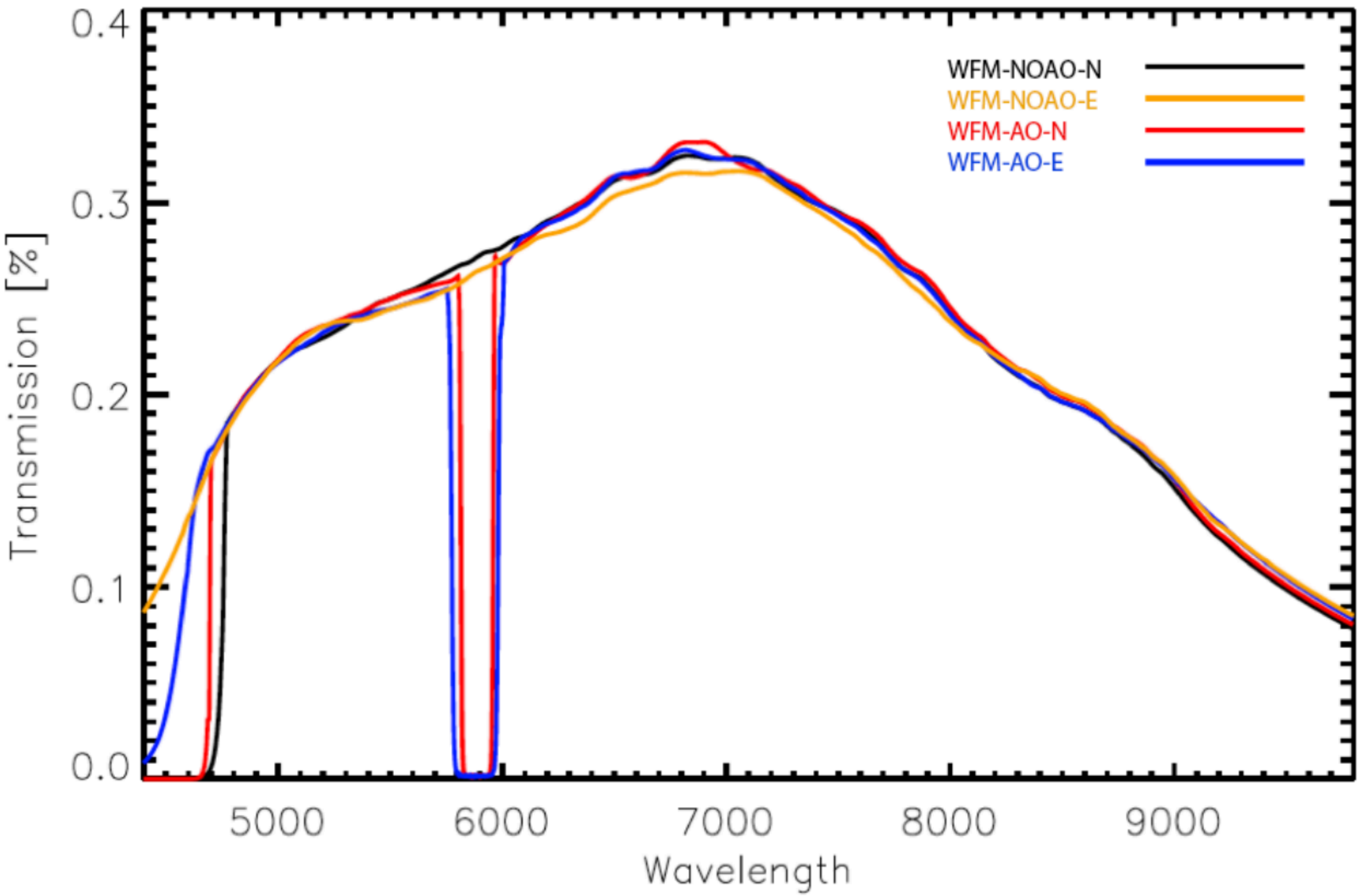
WFM-AO-E	WFM	Na	465-576, 601-930(*)
NFM-AO-N	NFM	Blue-IR	480-578, 605-930 Nota: the Na Notch filter is located in GALACSI

Nominal or Extended mode (N/E)

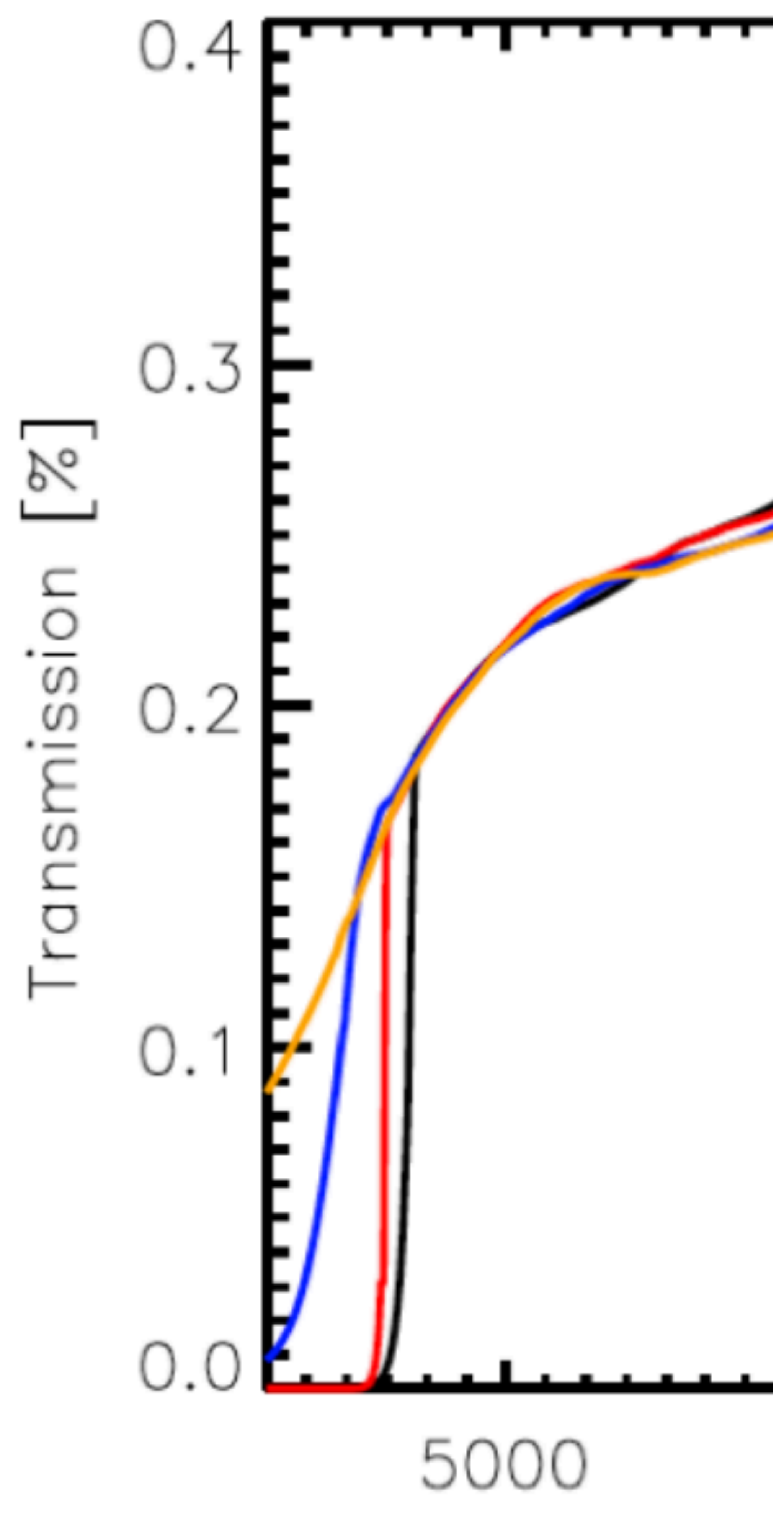
MUSE: Multi-Unit Spectroscopic Explorer

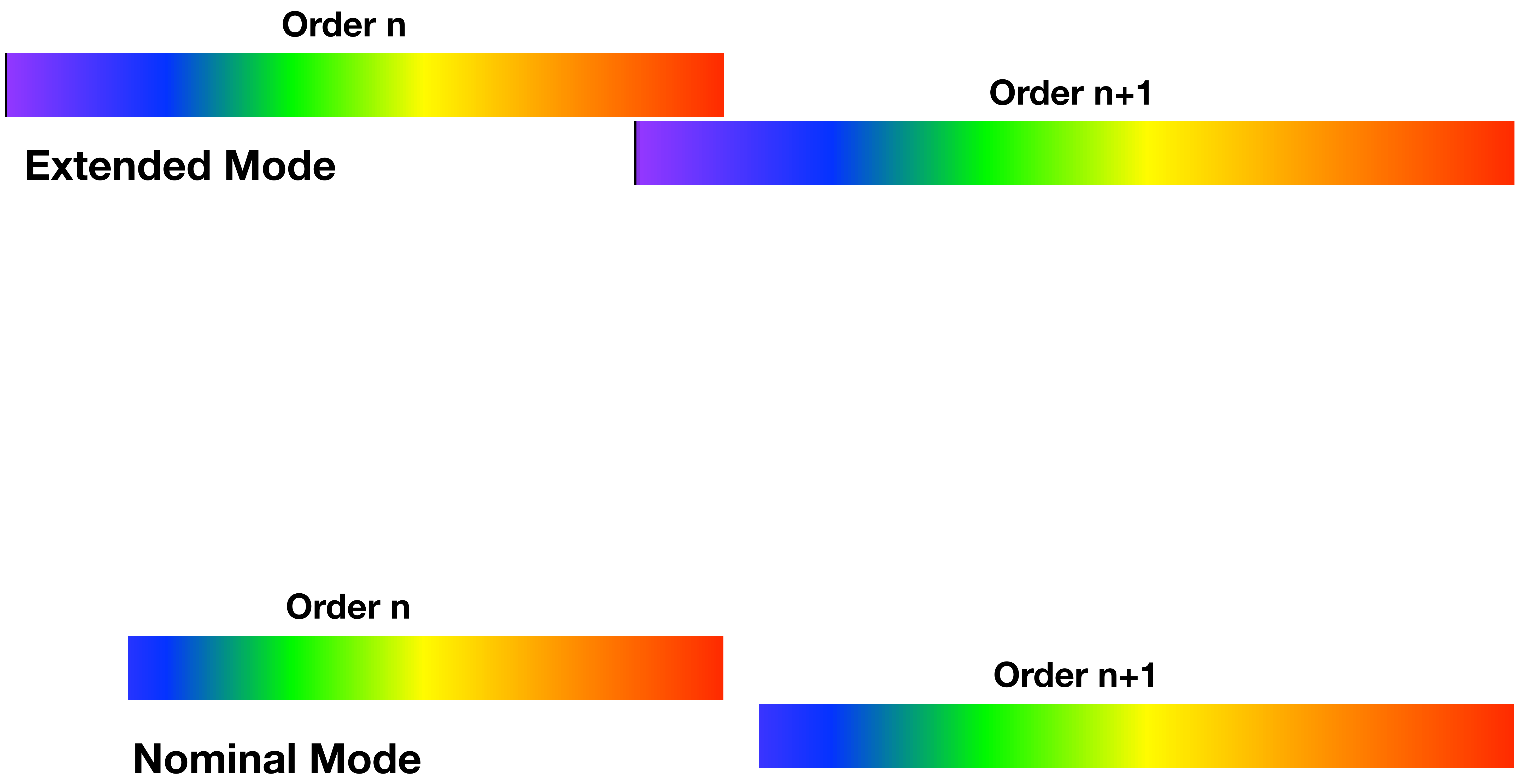
Extended and Nominal modes



MUSE: Multi-Unit Spectroscopic Explorer

Extended and Nominal modes

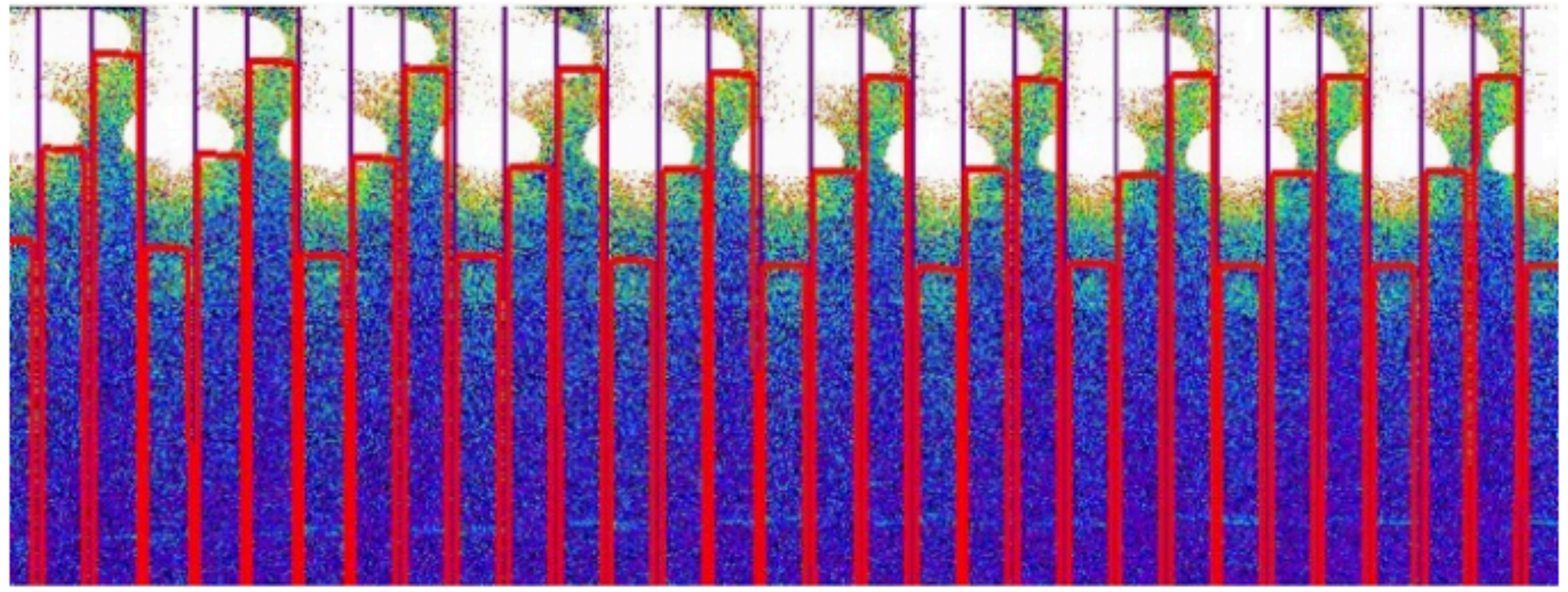




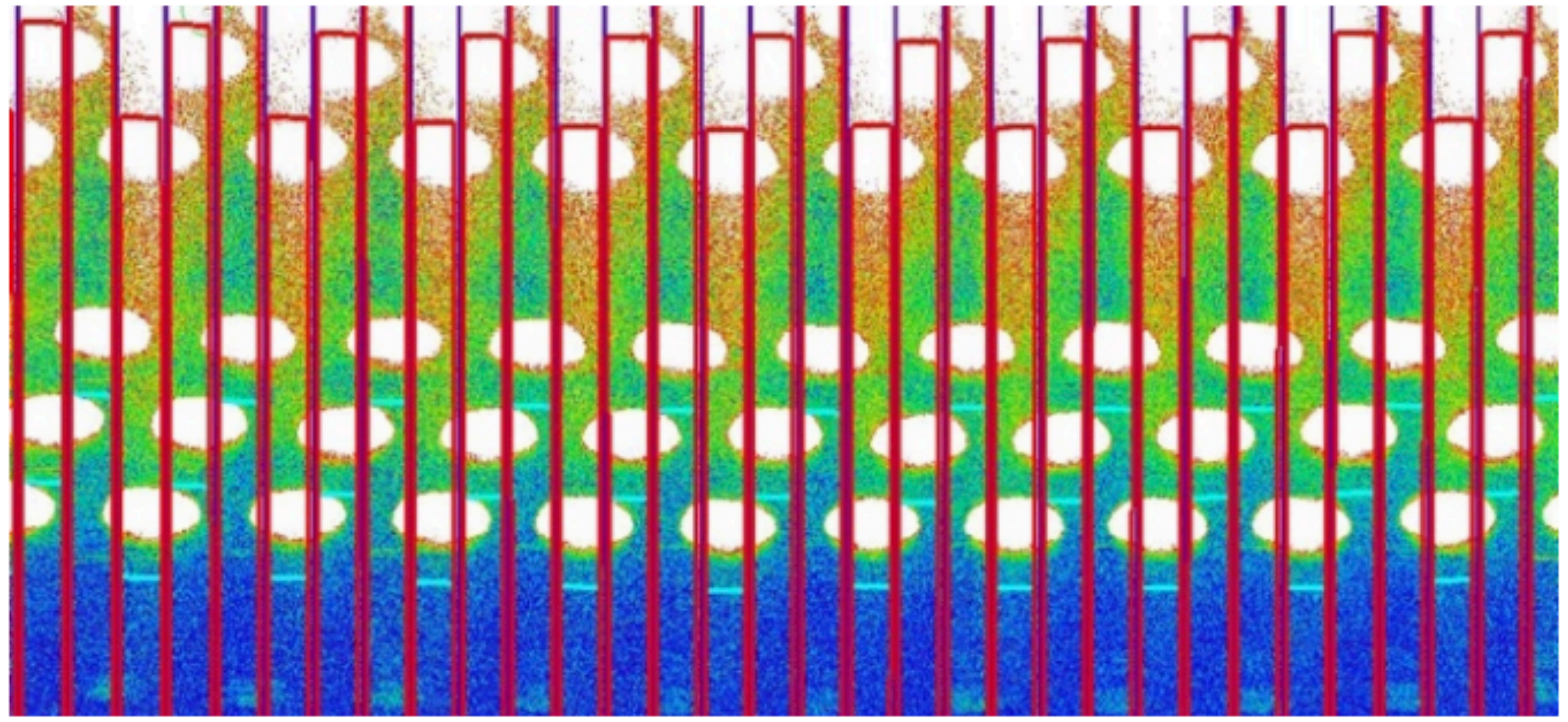
MUSE: Multi-Unit Spectroscopic Explorer

Wide Field Mode and Narrow Field Mode

Nominal Mode

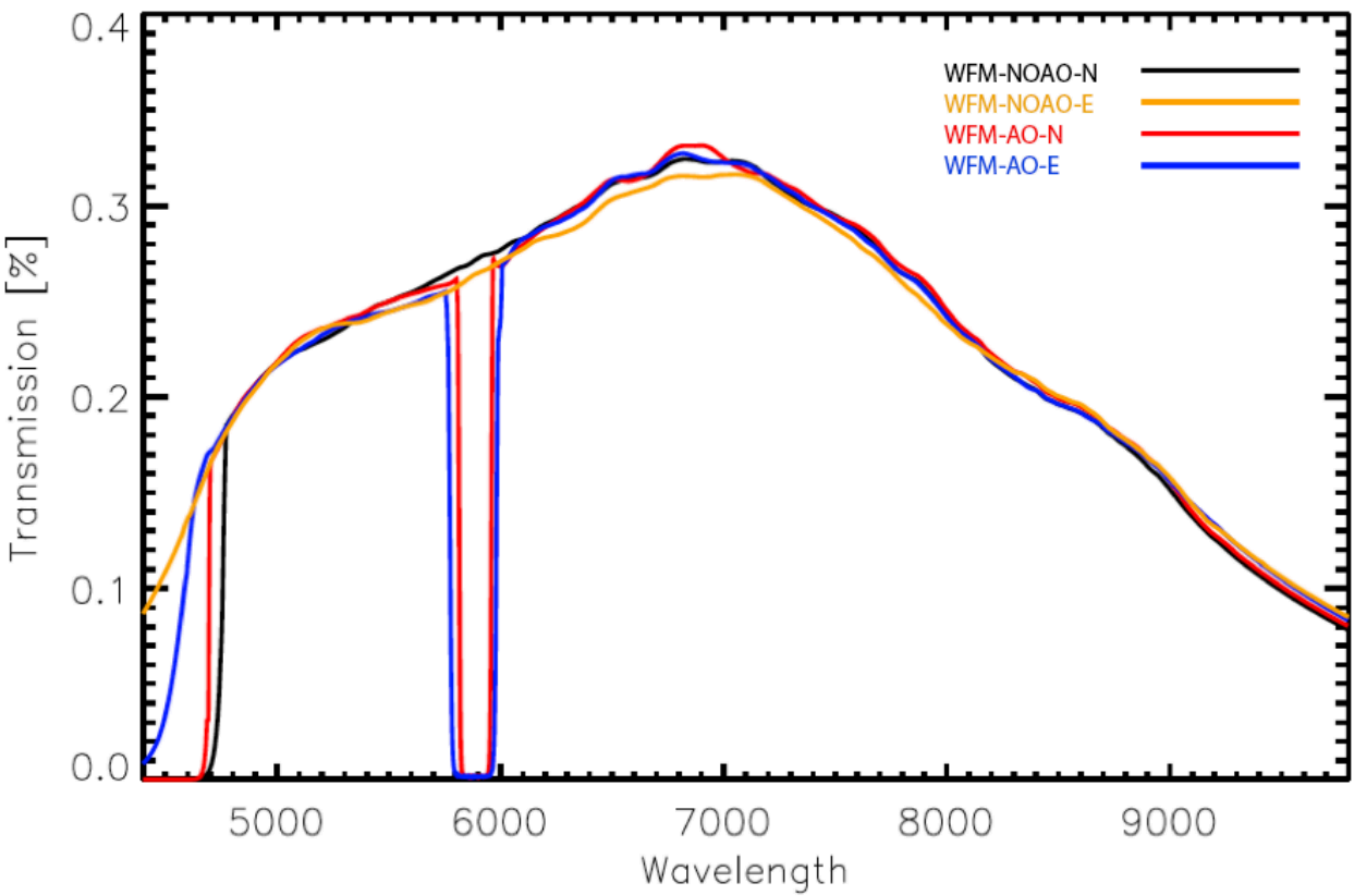


Extended Mode



MUSE: Multi-Unit Spectroscopic Explorer

Extended and Nominal modes



MUSE: Multi-Unit Spectroscopic Explorer

Raman Lines

Table 7 Raman Lines visible with MUSE with laser on.

Raman Line	λ4LGSF	CO_2	CO_2	O_2 (v1←0)	N_2 (v1←0)	CH_4	O_2 (v2←0)	H_2O	N_2 (v2←0)
Raman shift (cm–1)	…	1285.8	1388.1	1556.4	2330.7	2914.2	3089.2	3651.7	4631.2
λobs (Å)	5889.959	6372.57	6414.39	6484.39	6827.17	7110.43	7200.02	7503.93	8099.23
Flux	1.9×10^7	11.3	18.9	**6.8×10^3**	**2.0×10^4**	≲1.1	3.2	2.7	16.1

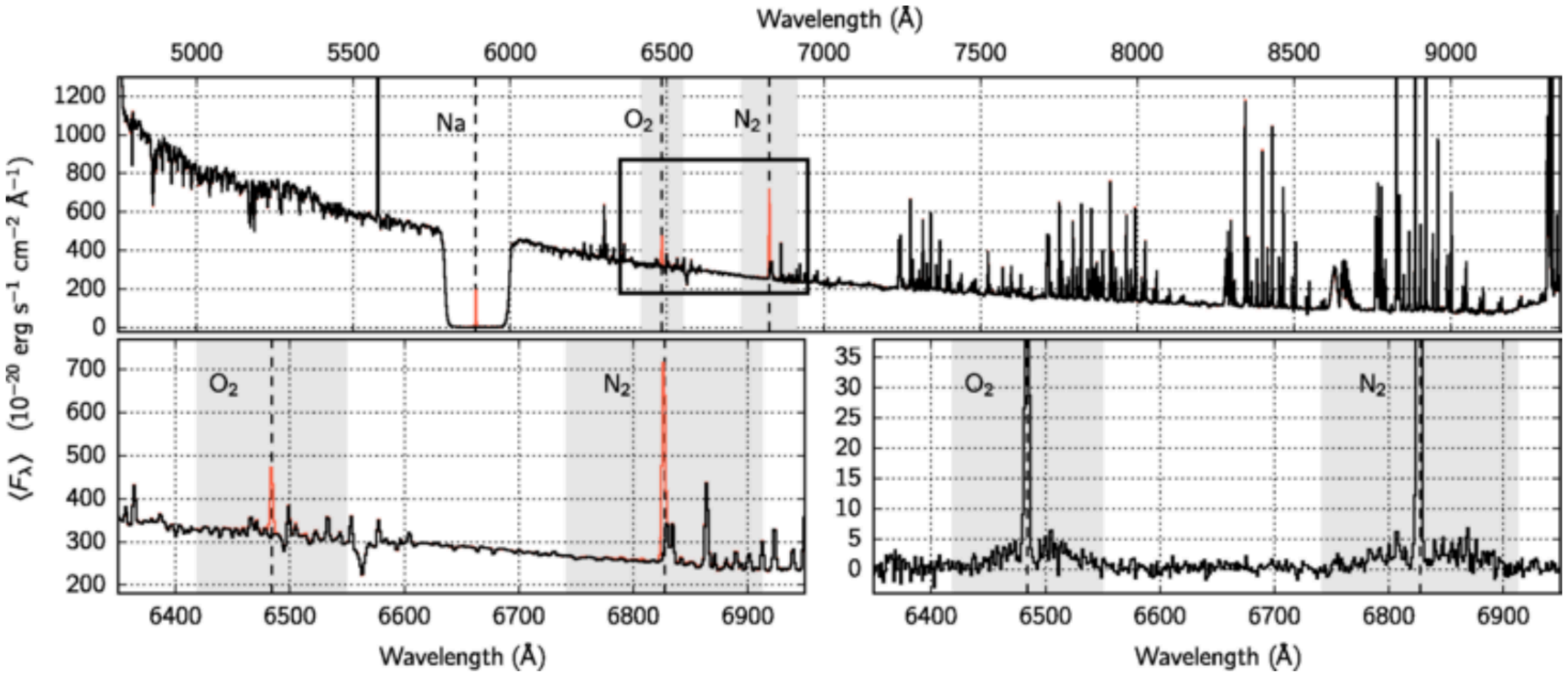


Figure 29 Sky spectrum seen by MUSE with 4LGSF on in WFM-AO mode.

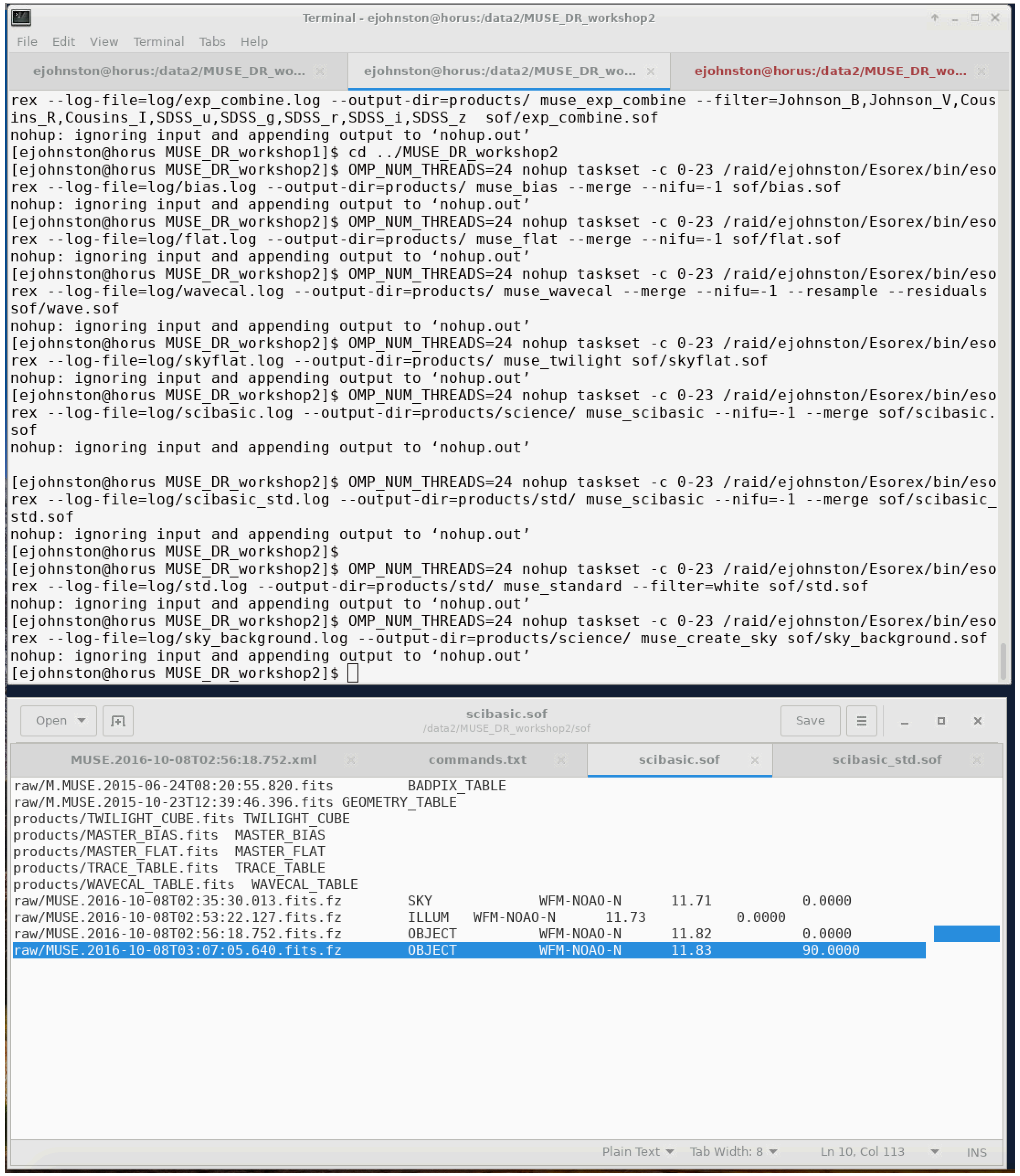
ESO Pipelines

ESOrex and ESO Reflex

ESO Data Reduction Pipelines

ESOrex

- Basic pipeline
- Used in the command line
- Pros:
  - Powerful tool
  - Easy to troubleshoot
- Cons
  - Harder to learn to use
  - YOU have to set up all the files
-



ESO Data Reduction Pipelines

ESO Reflex

- GUI (Graphical User Interface)
- 'Point and shoot' style
- Pros:
  - Easier to learn
  - Simply tell it where the data is, and it does everything
  - Supposedly more user-friendly
- Cons
  - Very much of a black box when it goes wrong
-

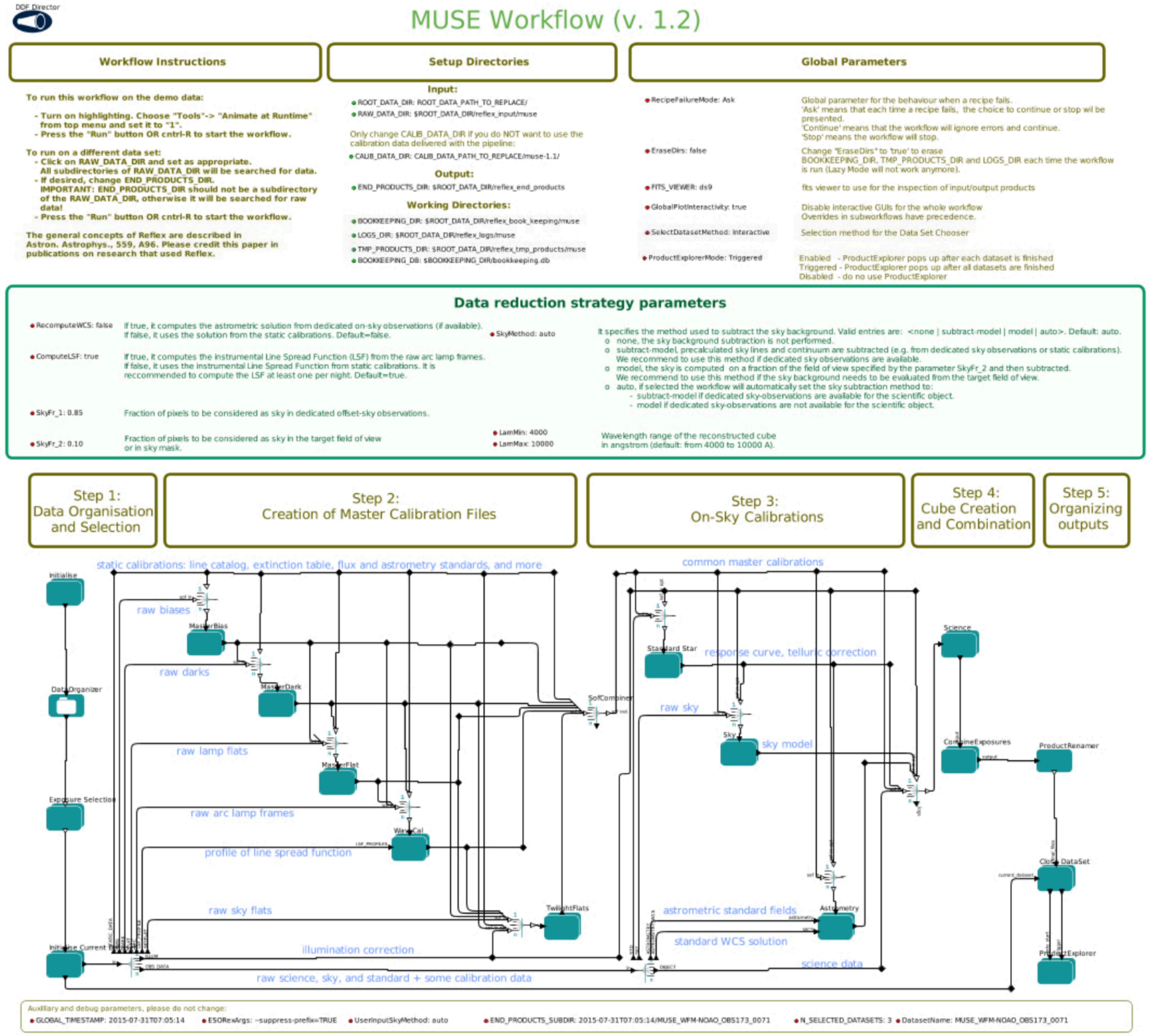


Image credit: MUSE user manual

ESO Data Reduction Pipelines

ESOrex *or* ESO Reflex

- This workshop will focus on **ESOrex**

My personal opinion/experience of using ESO Reflex:

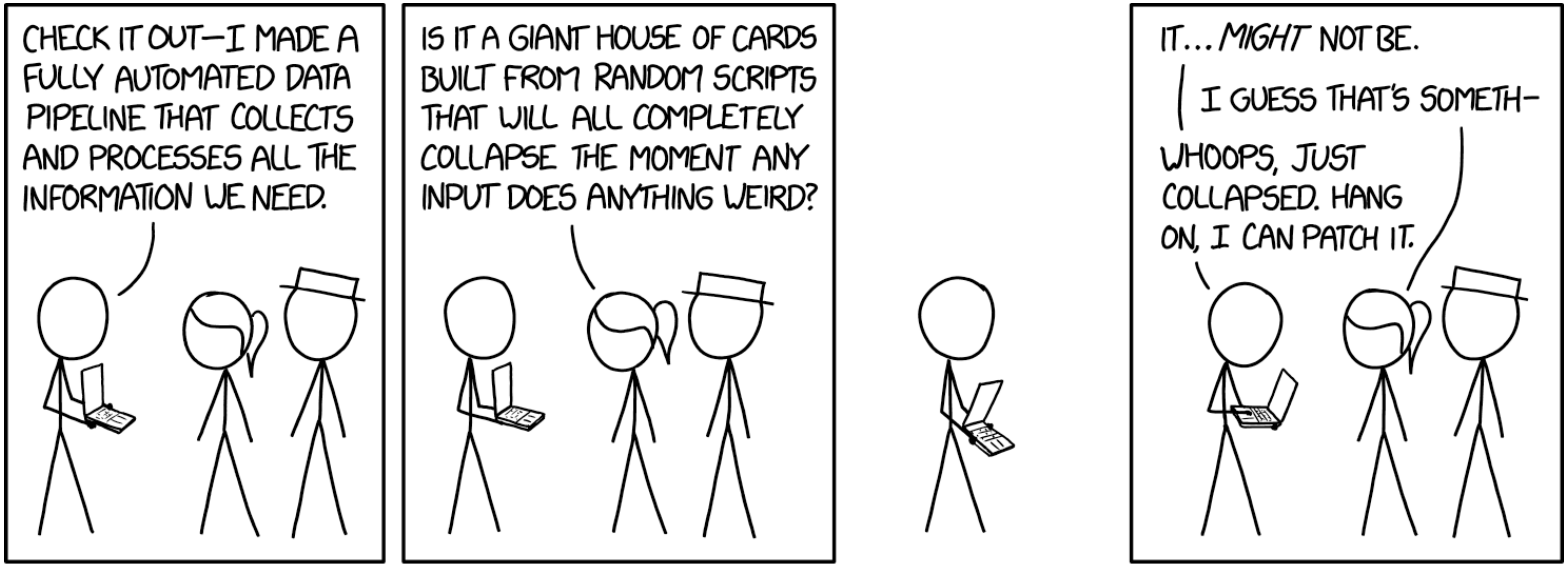
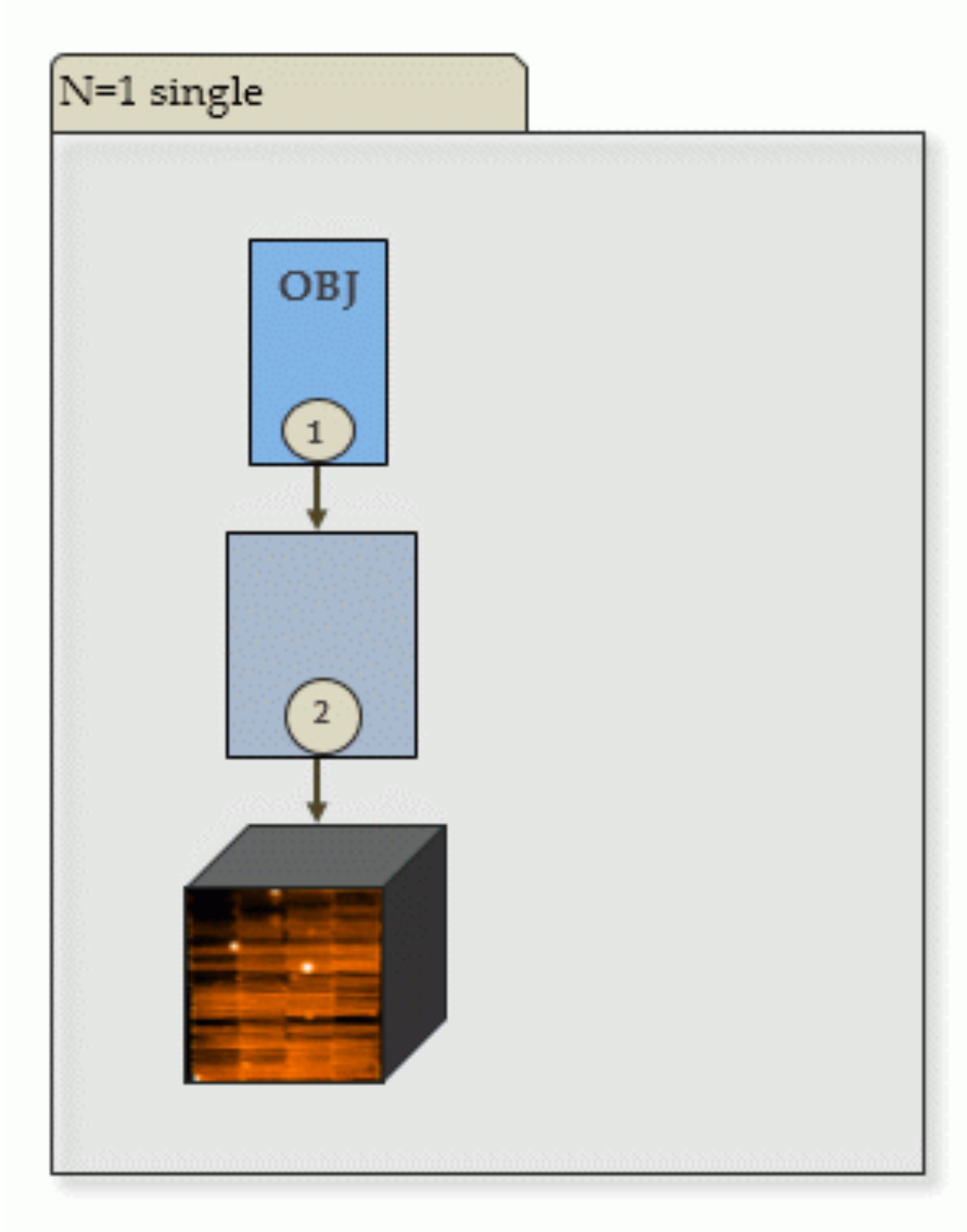


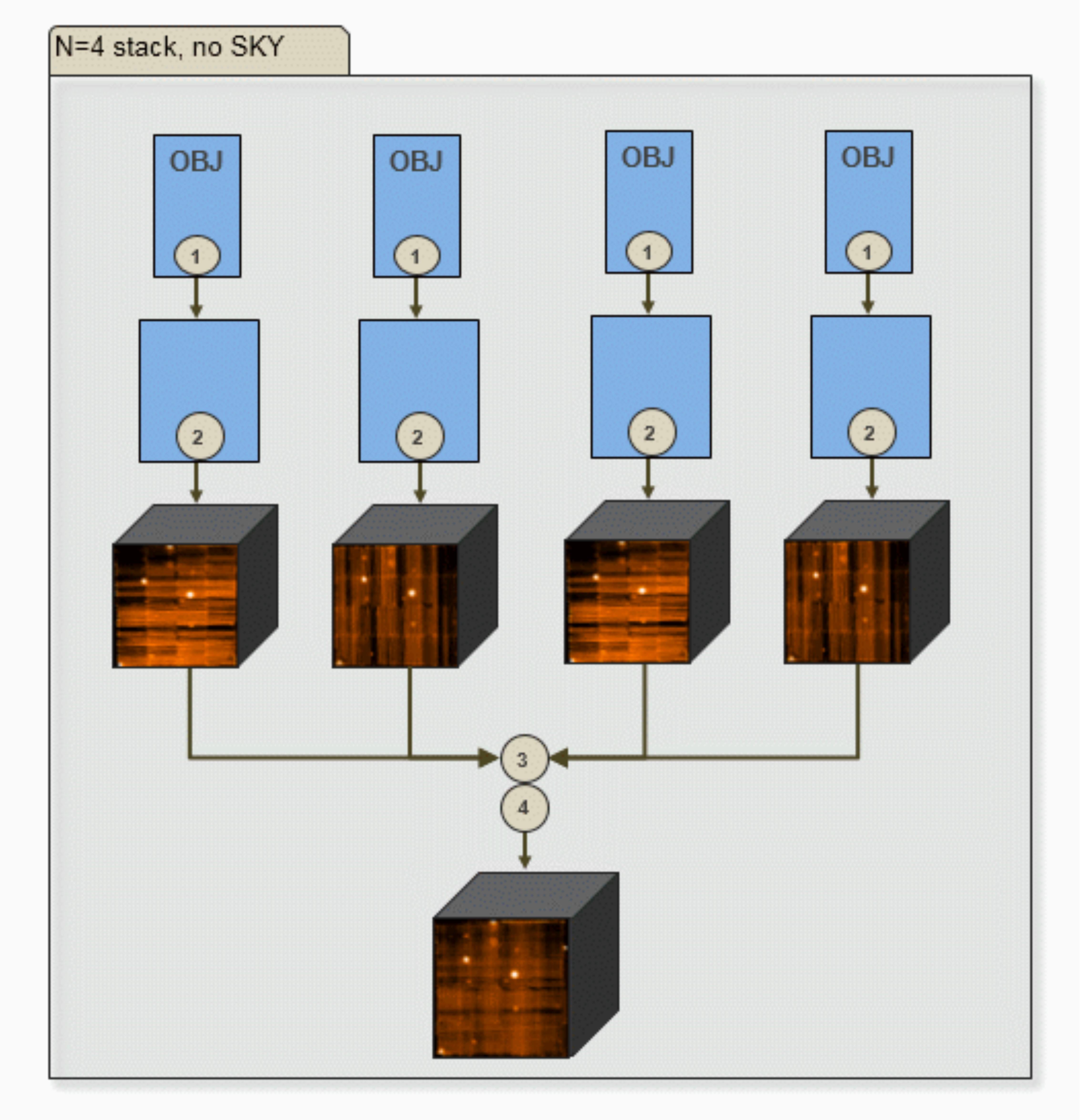
Image credit: xkcd.com/2054/

MUSE Data Reduction with ESOrex

MUSE Data Reduction

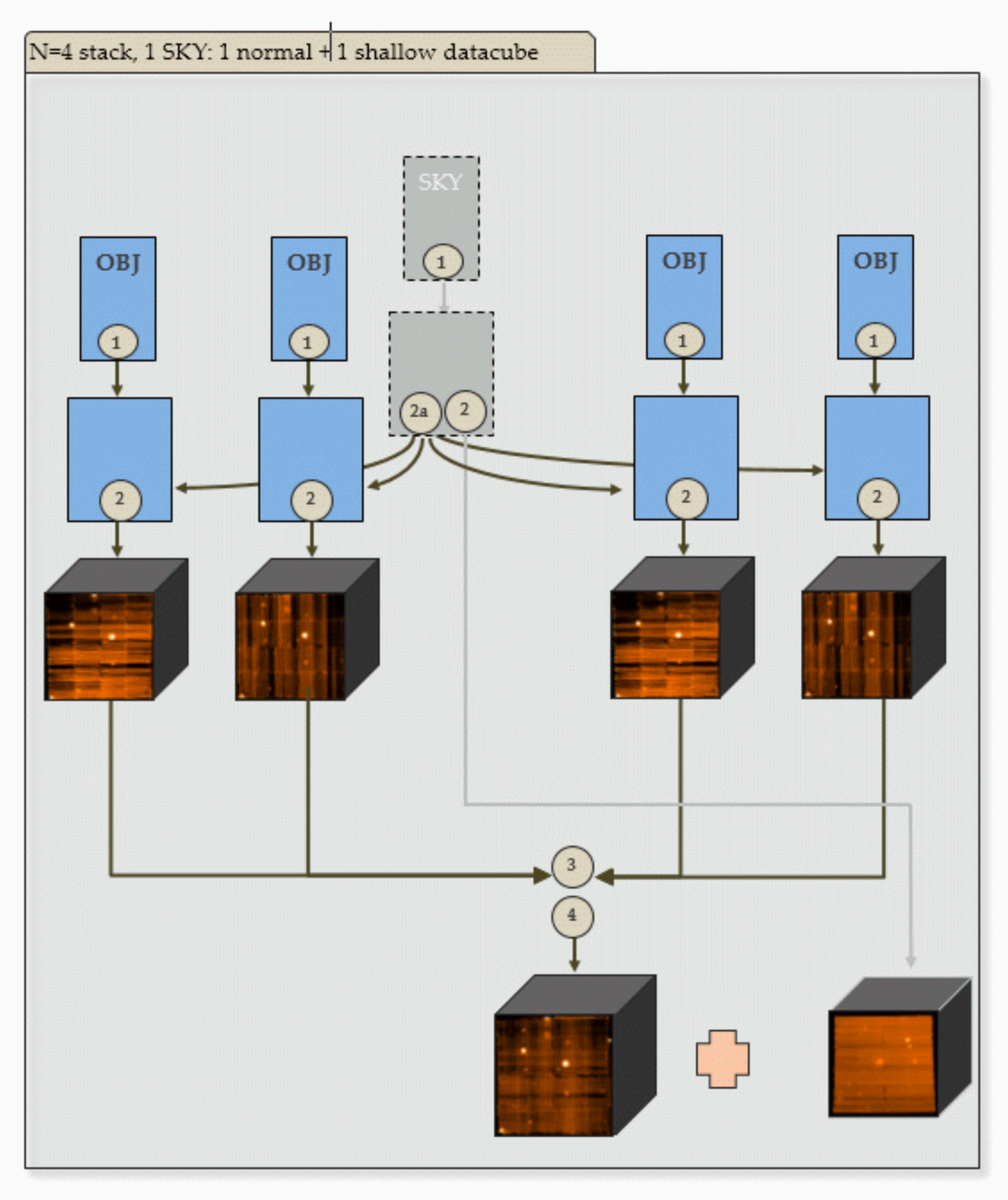
Observing Strategy

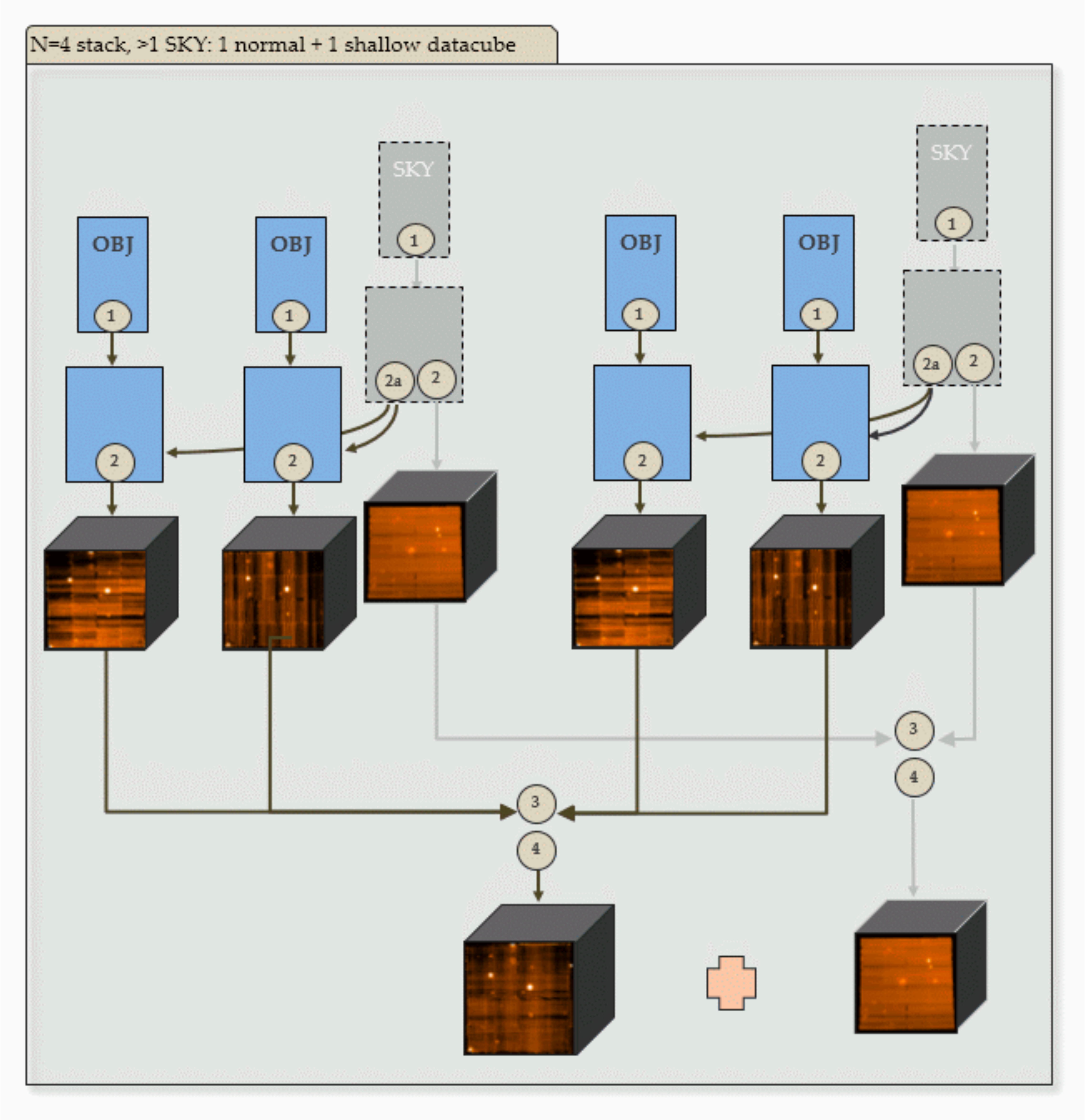




MUSE Data Reduction

Observing Strategy

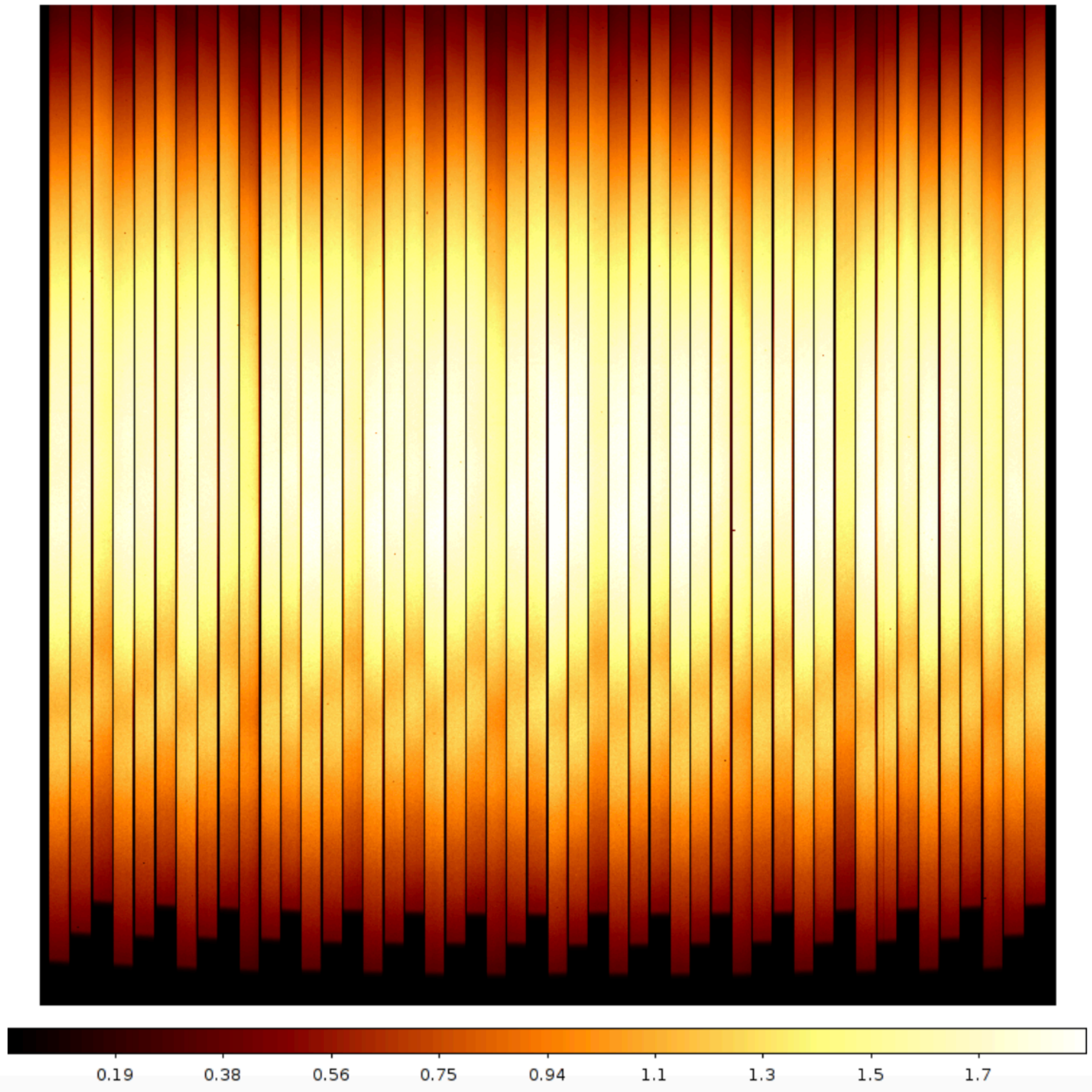




MUSE Data Reduction

Illumination Calibration

- Background levels in each CCD experience variations based on time and temperature variations.
- If not corrected for, final datacube is stripy
- Solution- lamp illumination calibrations, which are taken every hour or when the temperature within the instrument has changed significantly
-



MUSE Data Reduction

Computing Power

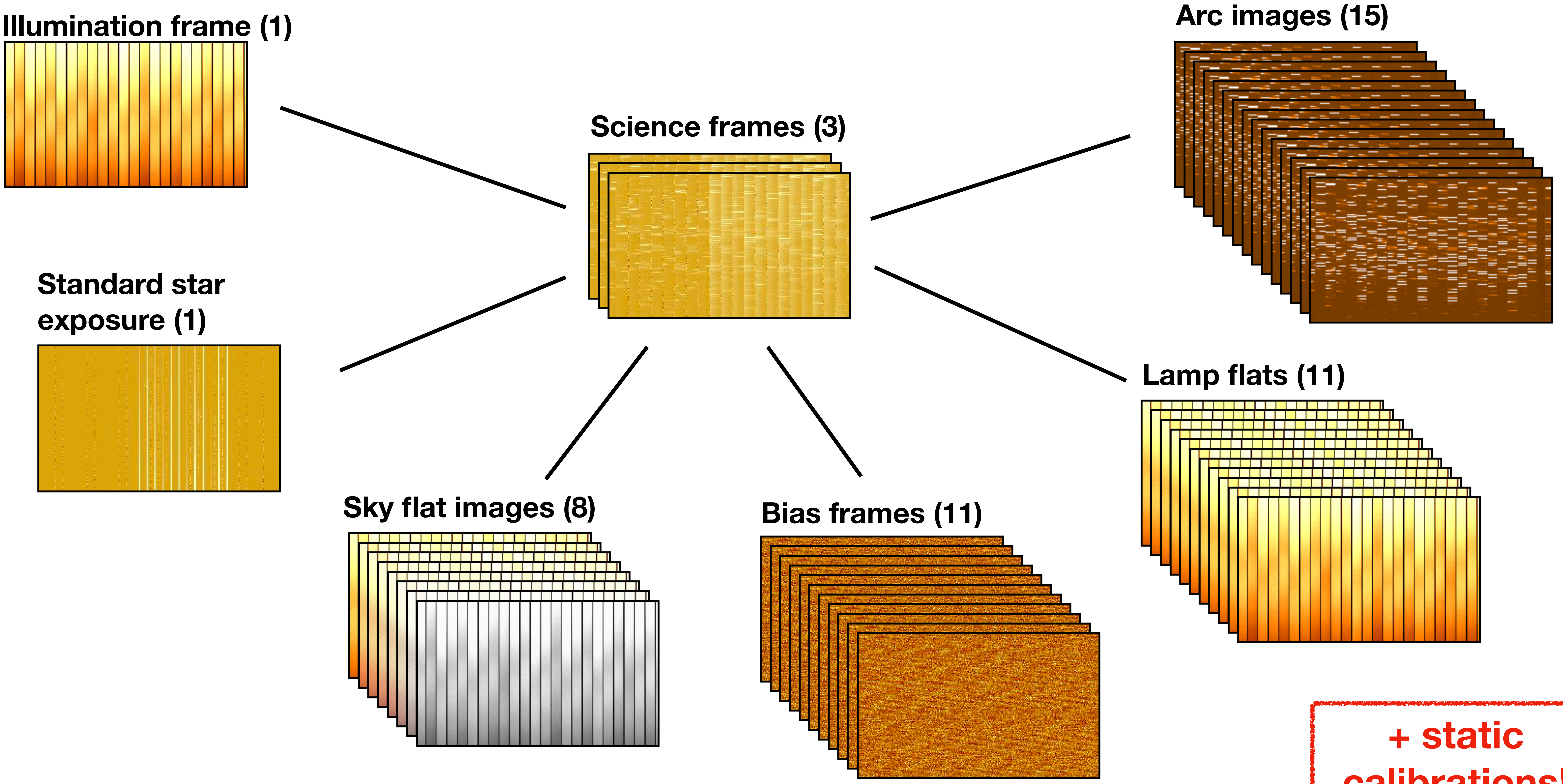
- MUSE data is **BIG**, Science data and calibrations for 1 OB can come to ~20-50GB, and the final datacube will be ~4GB.

- Minimum System Requirements
  - 32GB memory
  - 4 CPU cores
  - 1TB free space

- Recommended Configuration
  - 64GB memory
  - 24 CPU cores
  - 4TB free space

MUSE Data Reduction

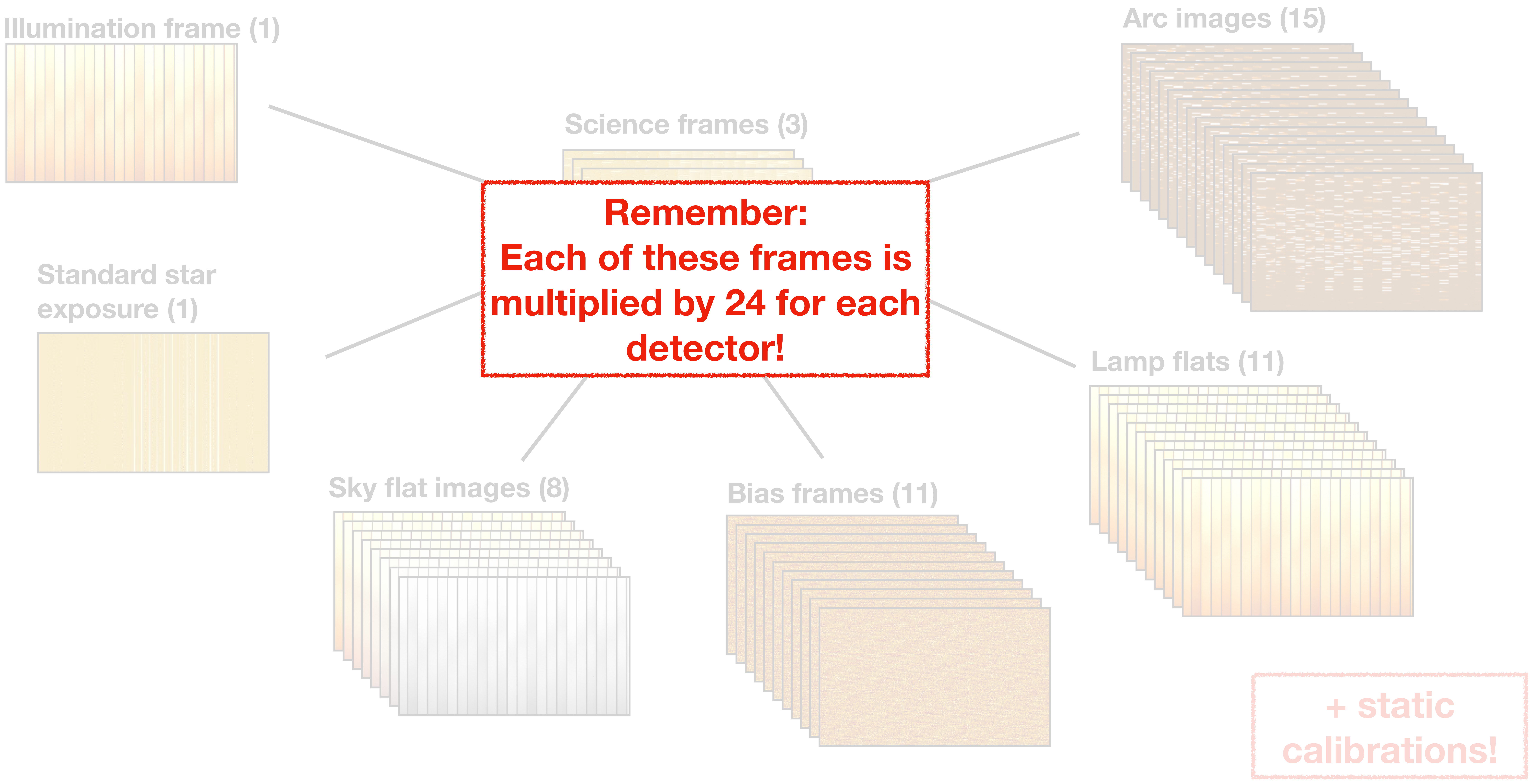
Why is MUSE data so big? Calibrations associated to 1 OB



+ static calibrations!

MUSE Data Reduction

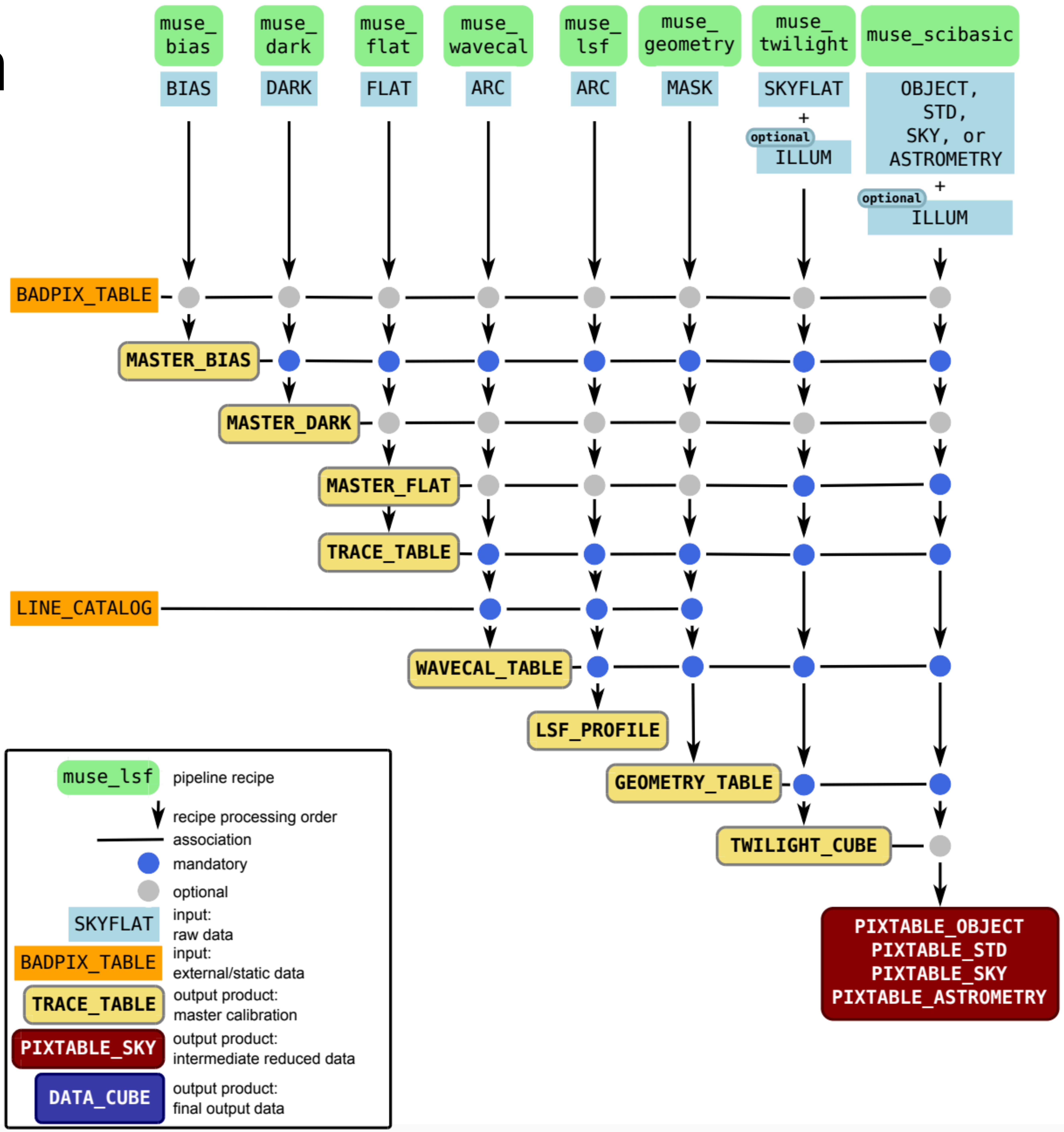
Why is MUSE data so big? Calibrations associated to 1 OB



MUSE Data Reduction

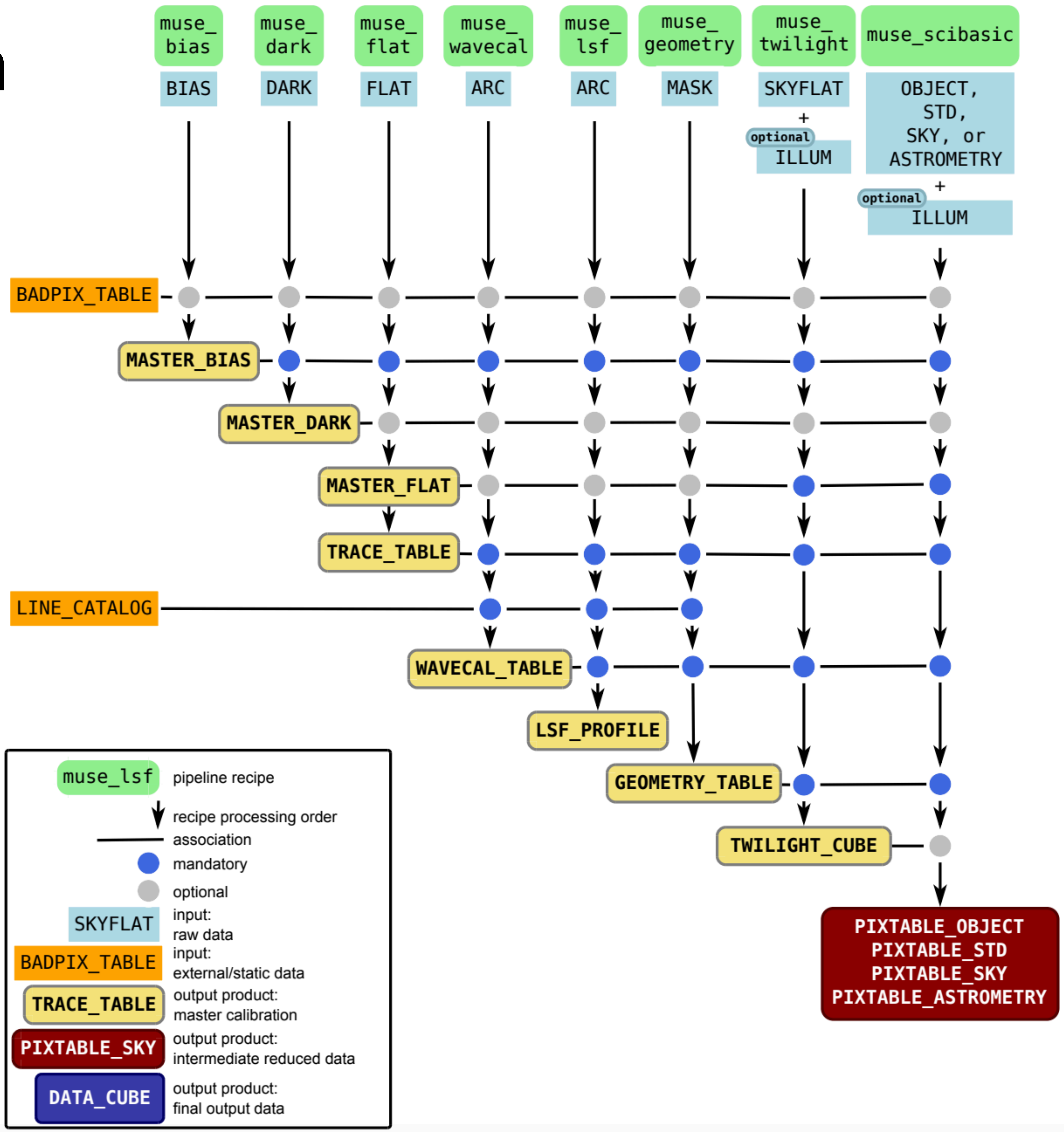
Pre-processing

- Basic DR steps
  - muse_bias
  - muse_dark
  - muse_flat
  - muse_wavecal
  - muse_lsf
  - muse_geometry
  - muse_twilight
  - muse_scibasic



MUSE Data Reduction
Pre-processing

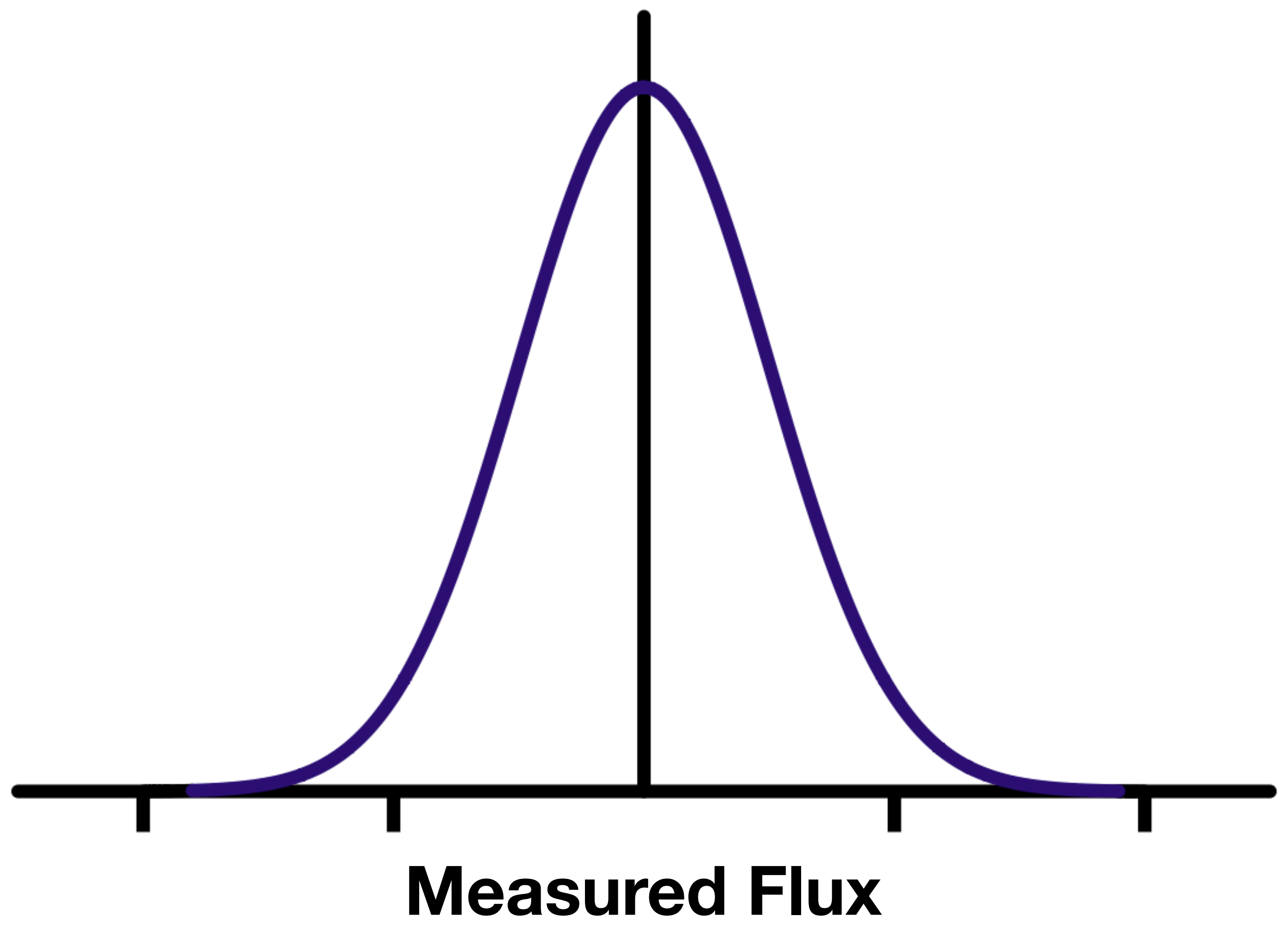
- Basic DR steps
  - muse_bias
  - muse_dark
  - muse_flat
  - muse_wavecal
  - muse_lsf
  - muse_geometry
  - muse_twilight
  - muse_scibasic

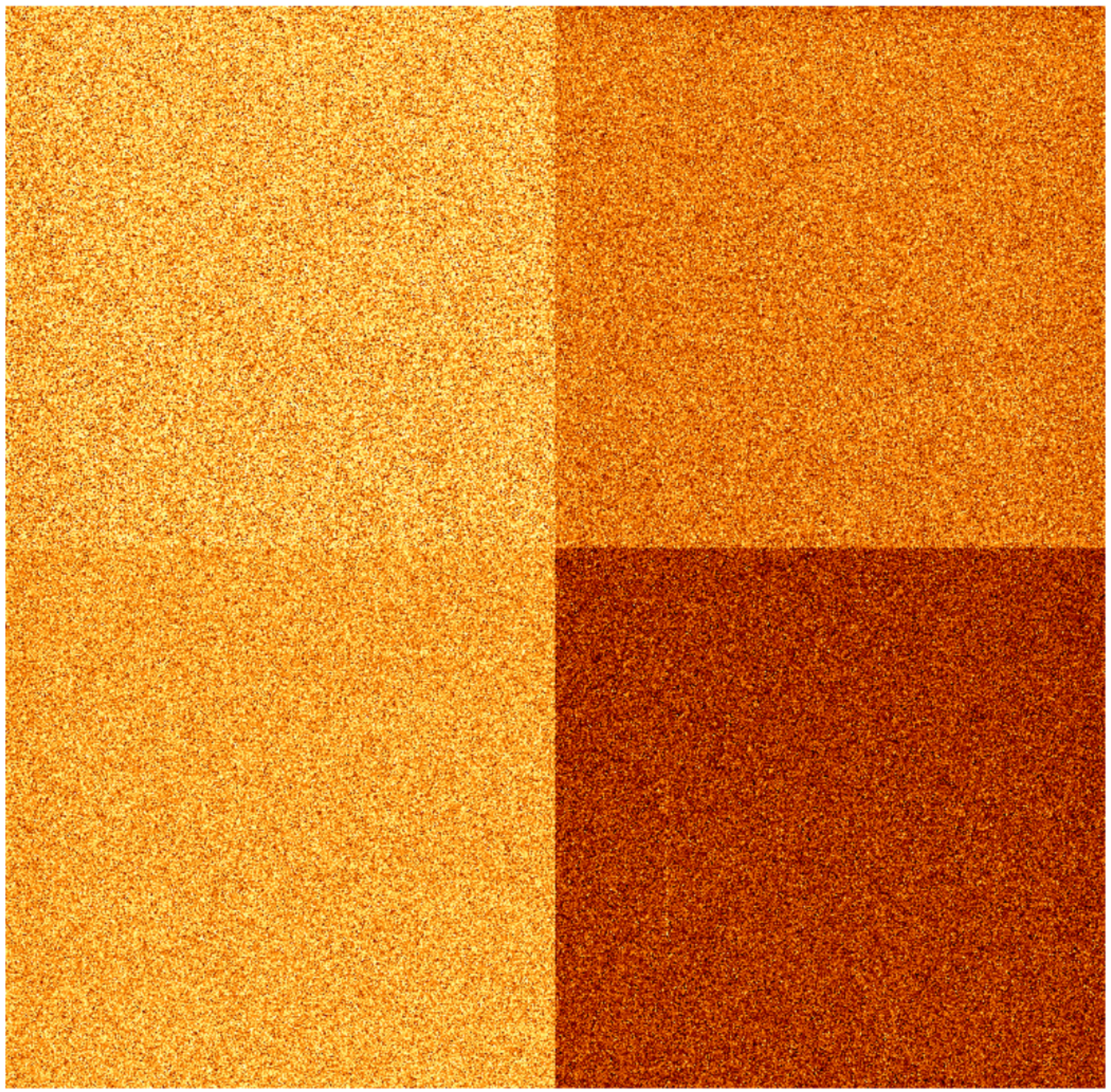


MUSE Data Reduction

muse_bias

- **Creates the Master Bias frame**
- 11 zero-second exposures
- Median stack the images
- The final image shows the read-out noise and bias level per pixel, and the locations of hot or dead pixels.
-

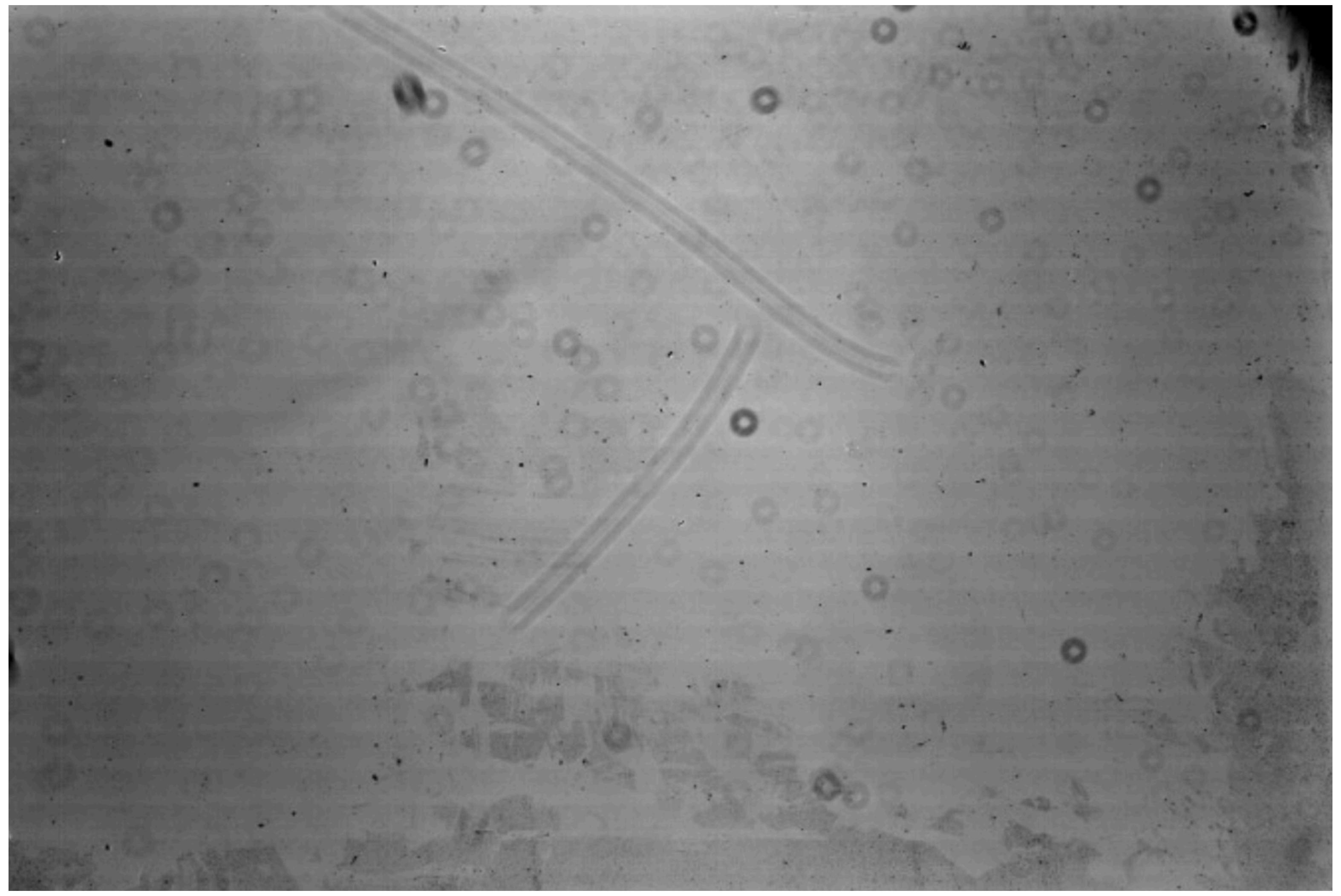


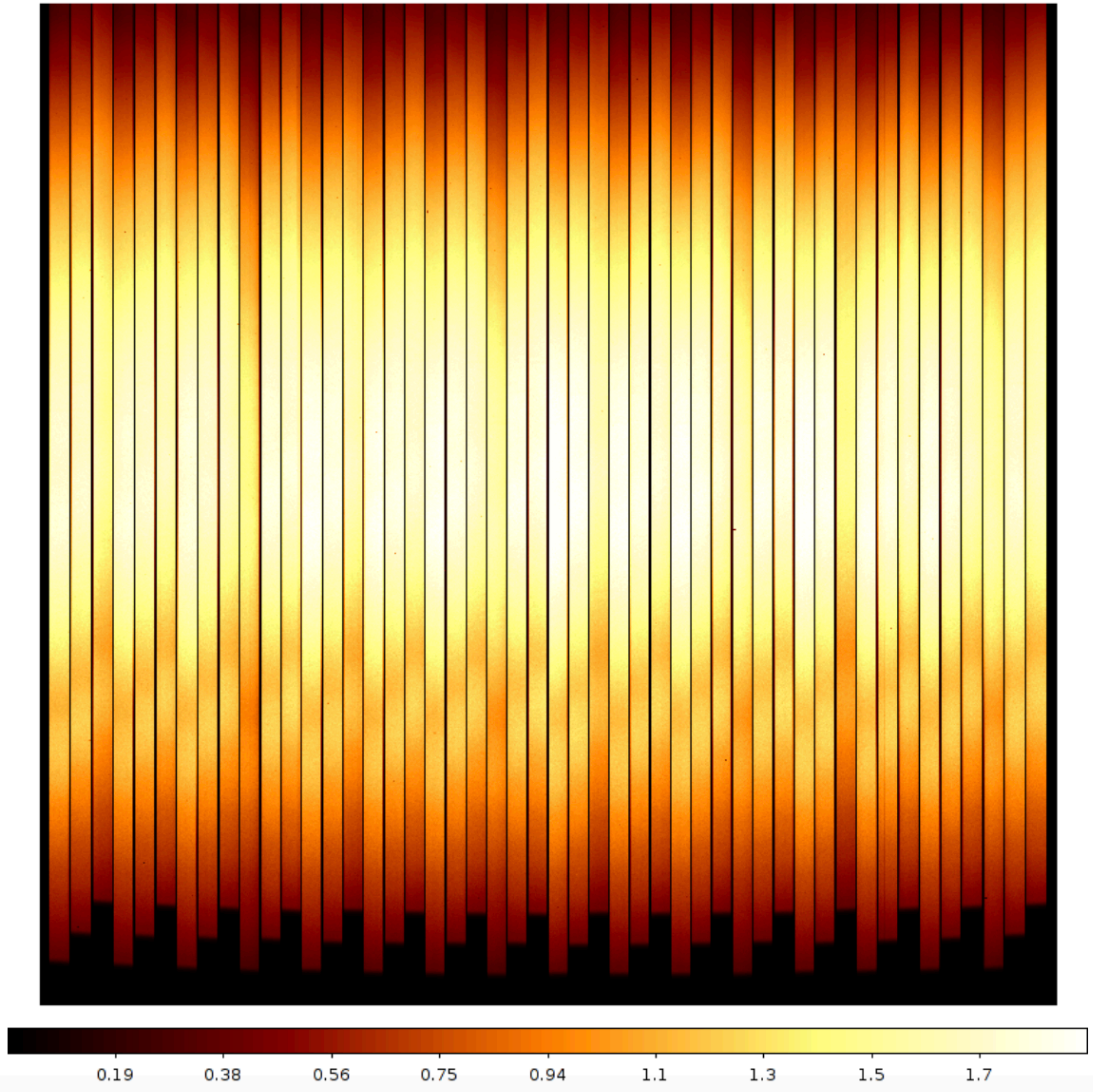


MUSE Data Reduction

muse_flat

- **Creates the Master Flat Field/Trace Table**
- 11 exposures of a lamp, giving uniform illumination across the entire CCD
- Used to identify variations in the pixel sensitivity, e.g. hot/dead pixels, dust etc
- In MUSE pipeline, also traces the spectra for each slitlet
-



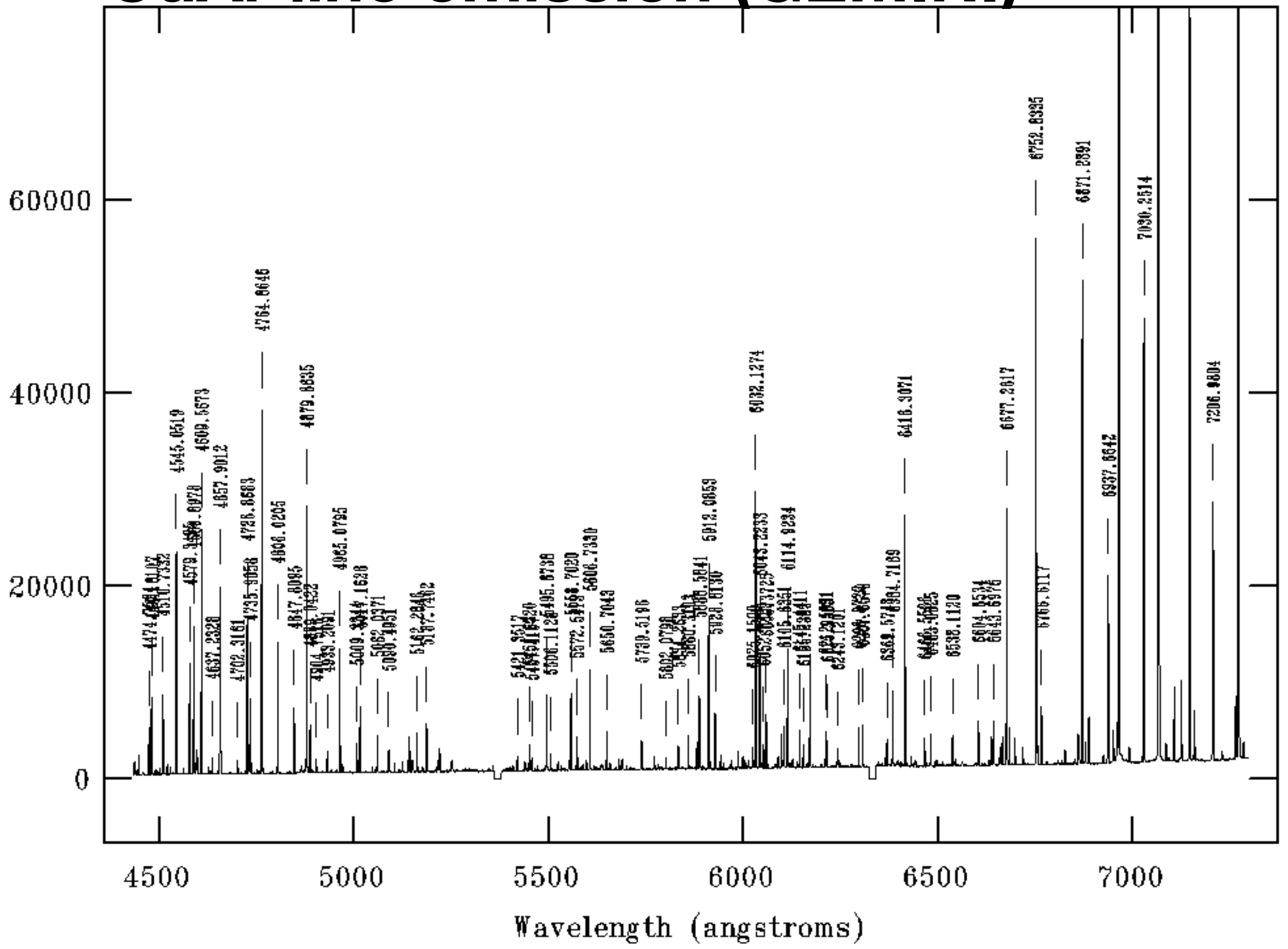


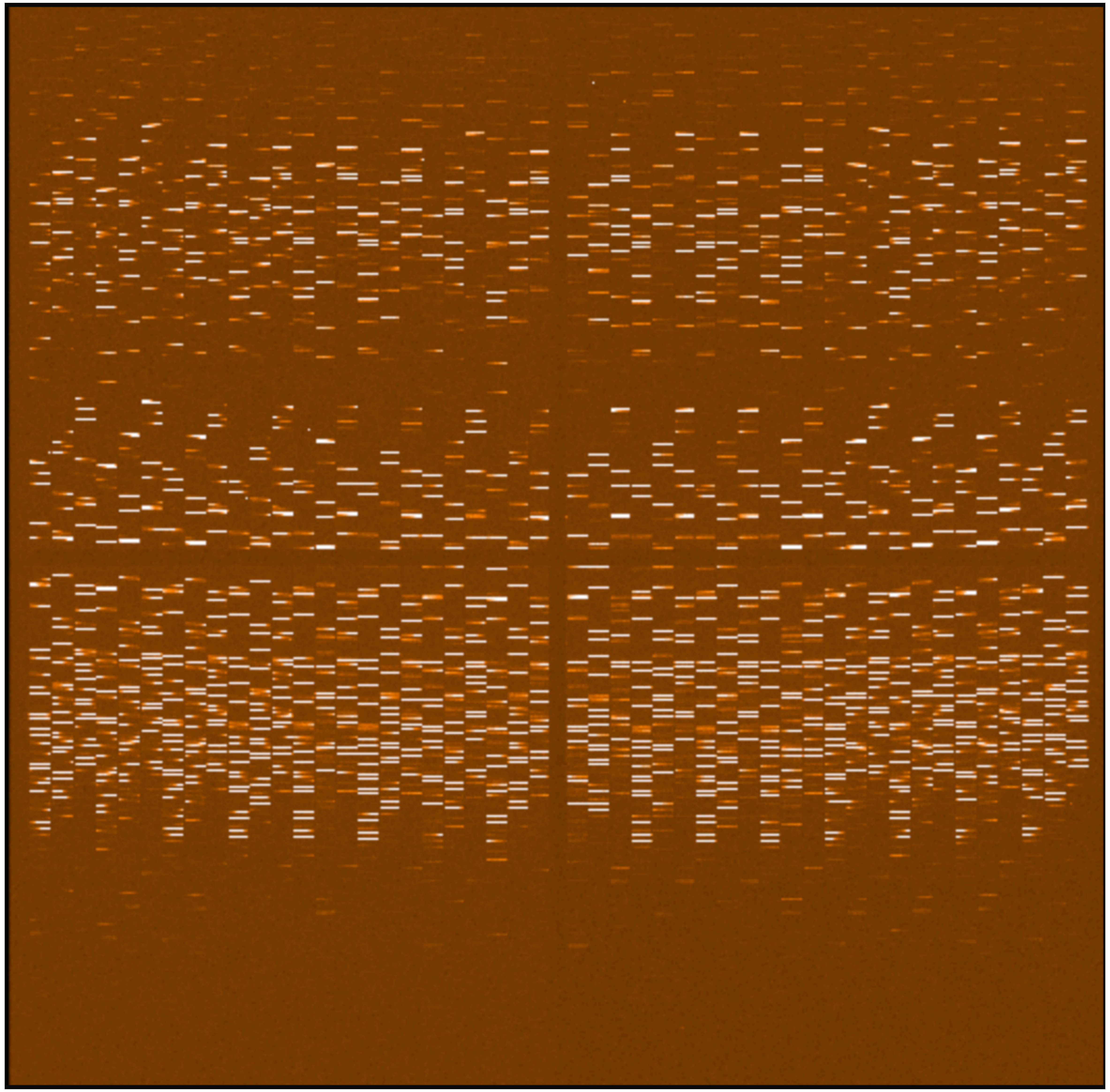
MUSE Data Reduction

muse_wavecal

- **Creates the Wavelength Calibration**
- 15 exposures using 3 arc lamps
- Each arc lamp produced emission lines at known wavelengths
- The pipeline looks for these emission lines on the CCD, and calculates the wavelength calibration

CuAr line emission (GEMINI)

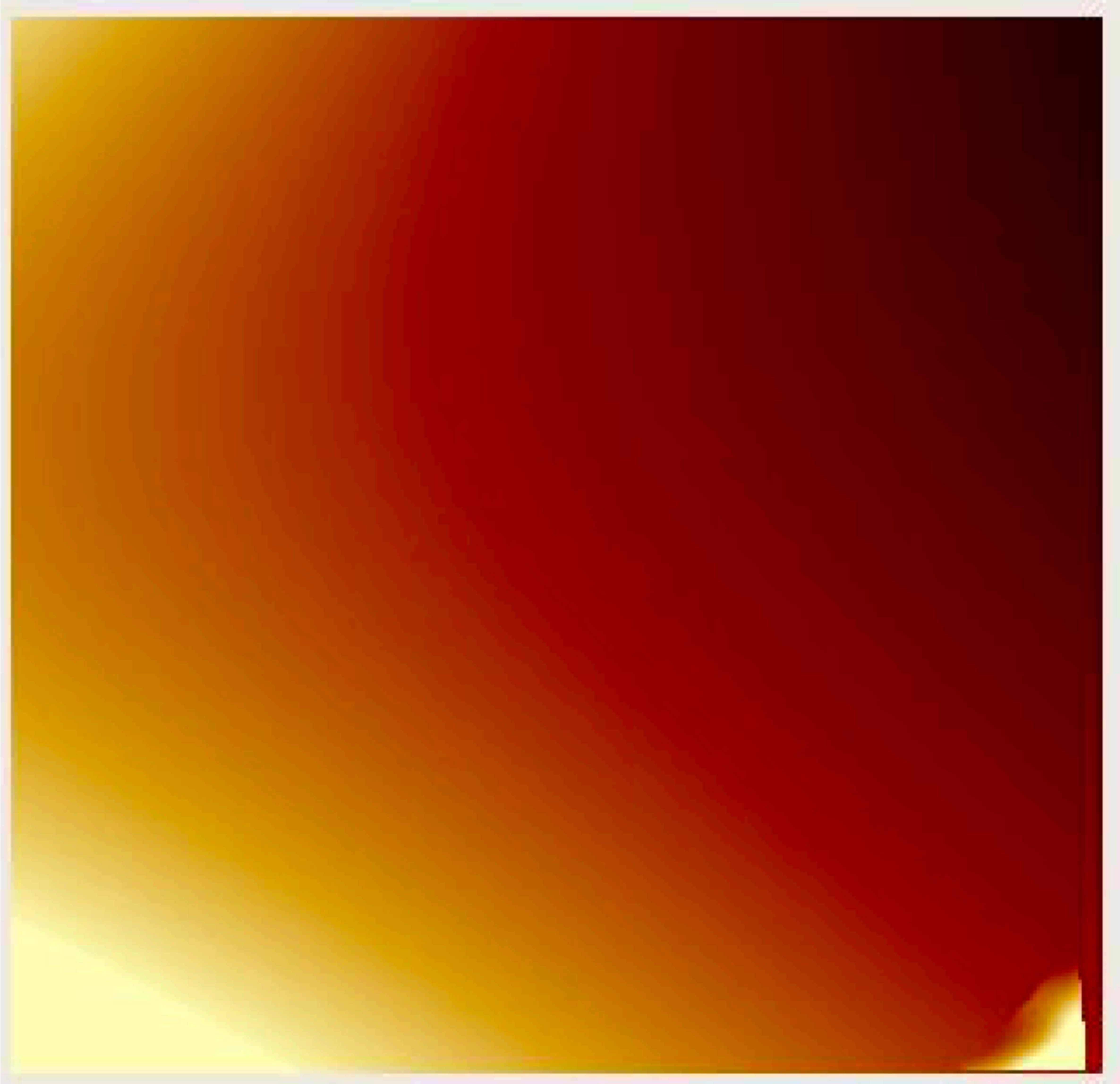




MUSE Data Reduction

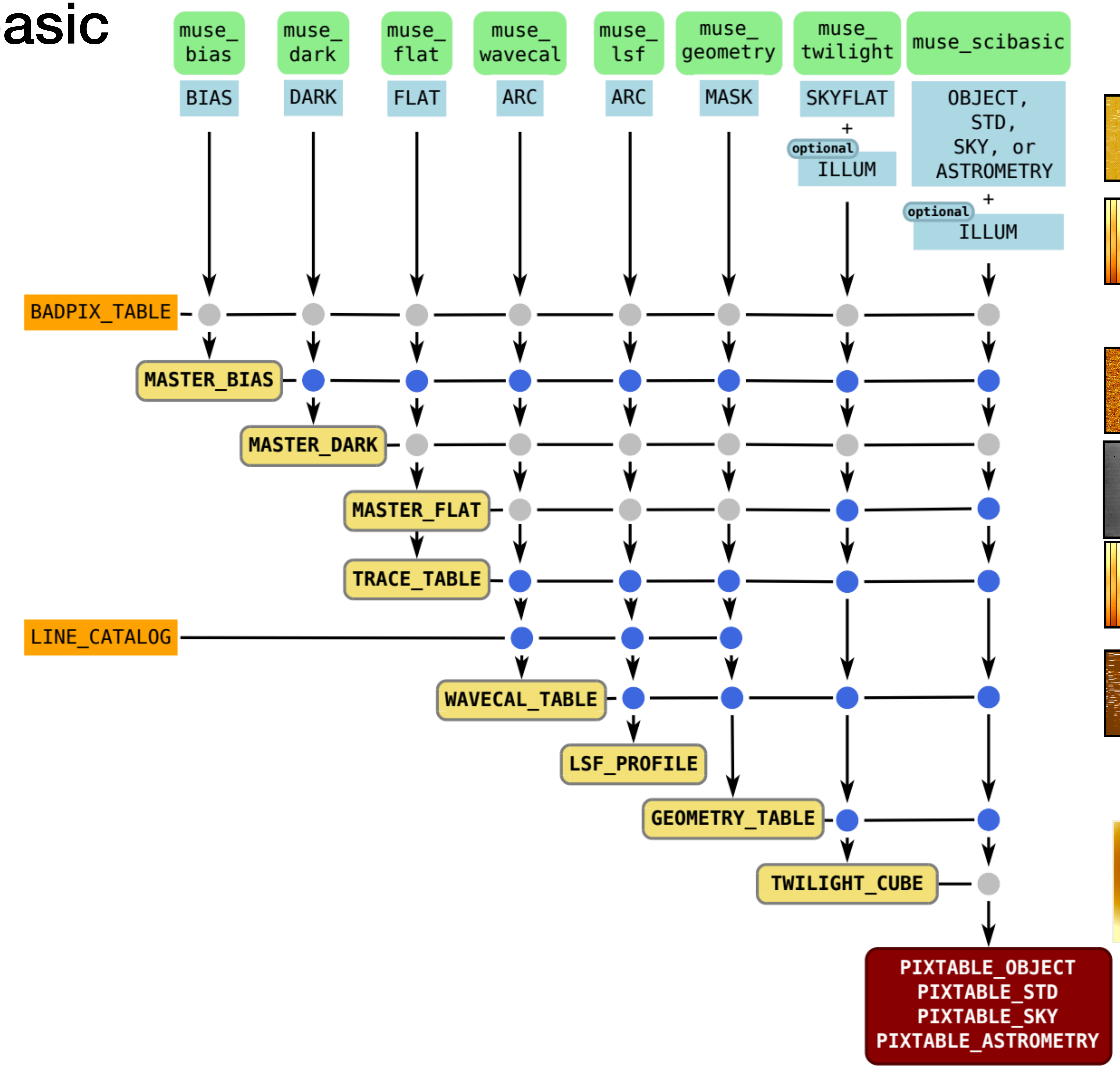
muse_twilight

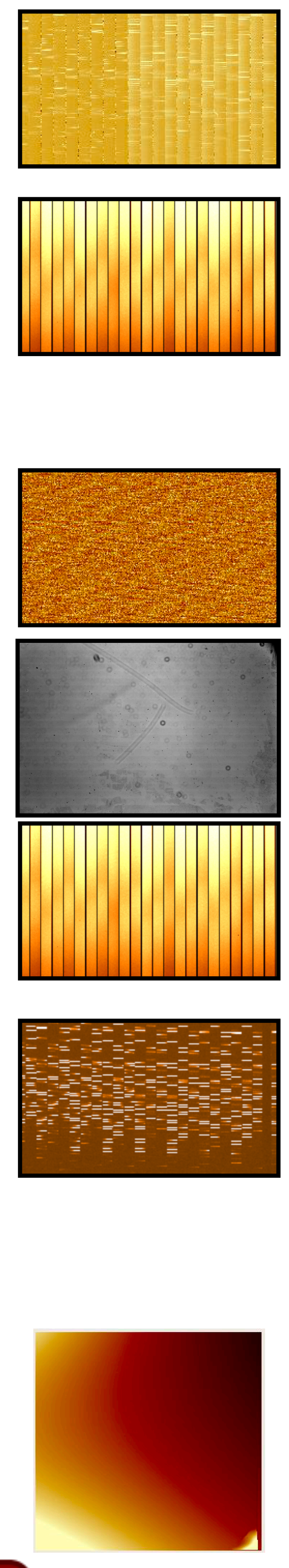
- **Creates the Twilight Cube**
- 8 exposures of an empty field during twilight
- Each image has a different exposure time and flux level
- CCD should be illuminated uniformly, so this calibration corrects for differences in the flat fielding between detectors
- 3D illumination correction



MUSE Data Reduction

muse_scibasic





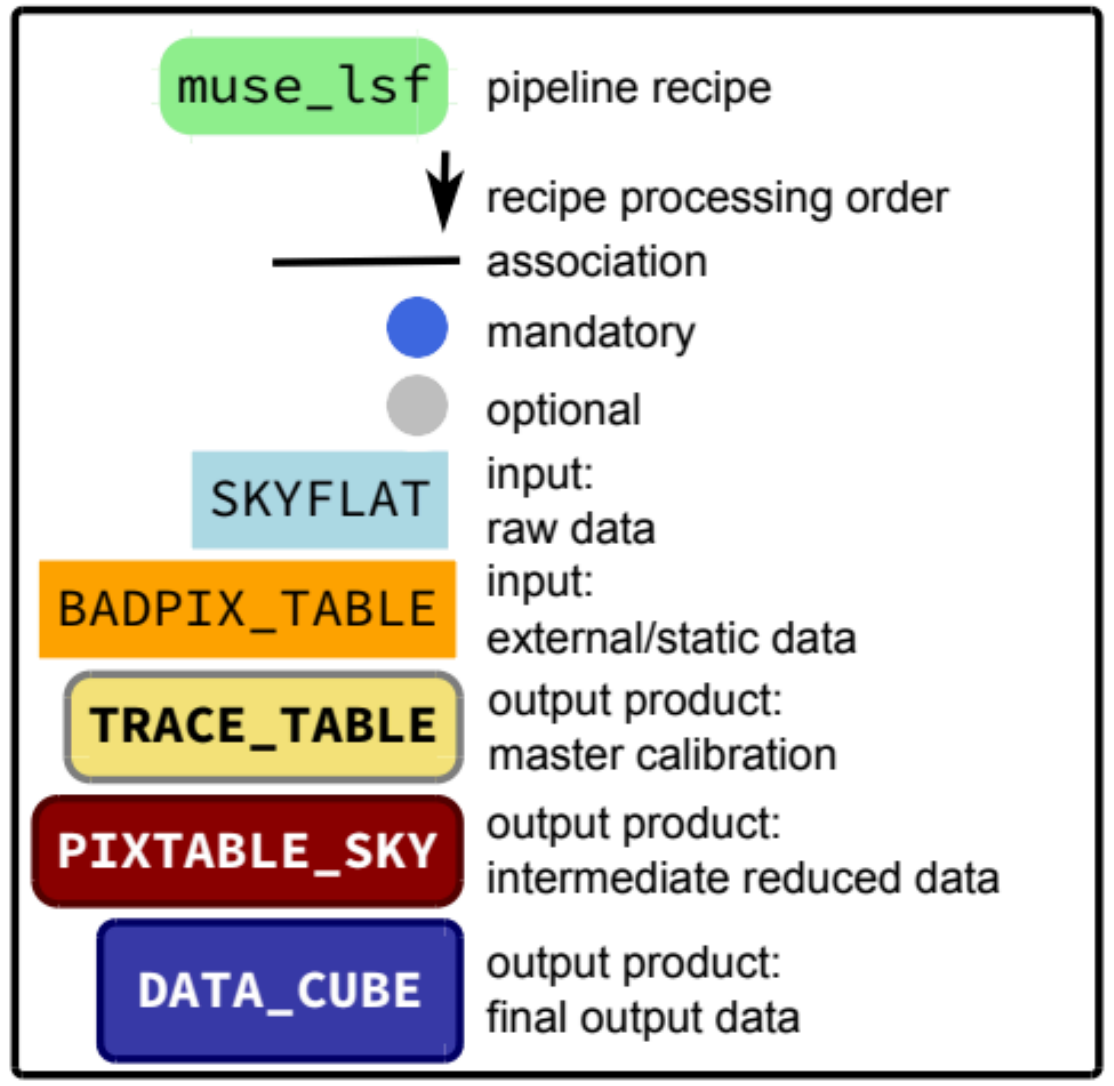
Applied to each CCD image

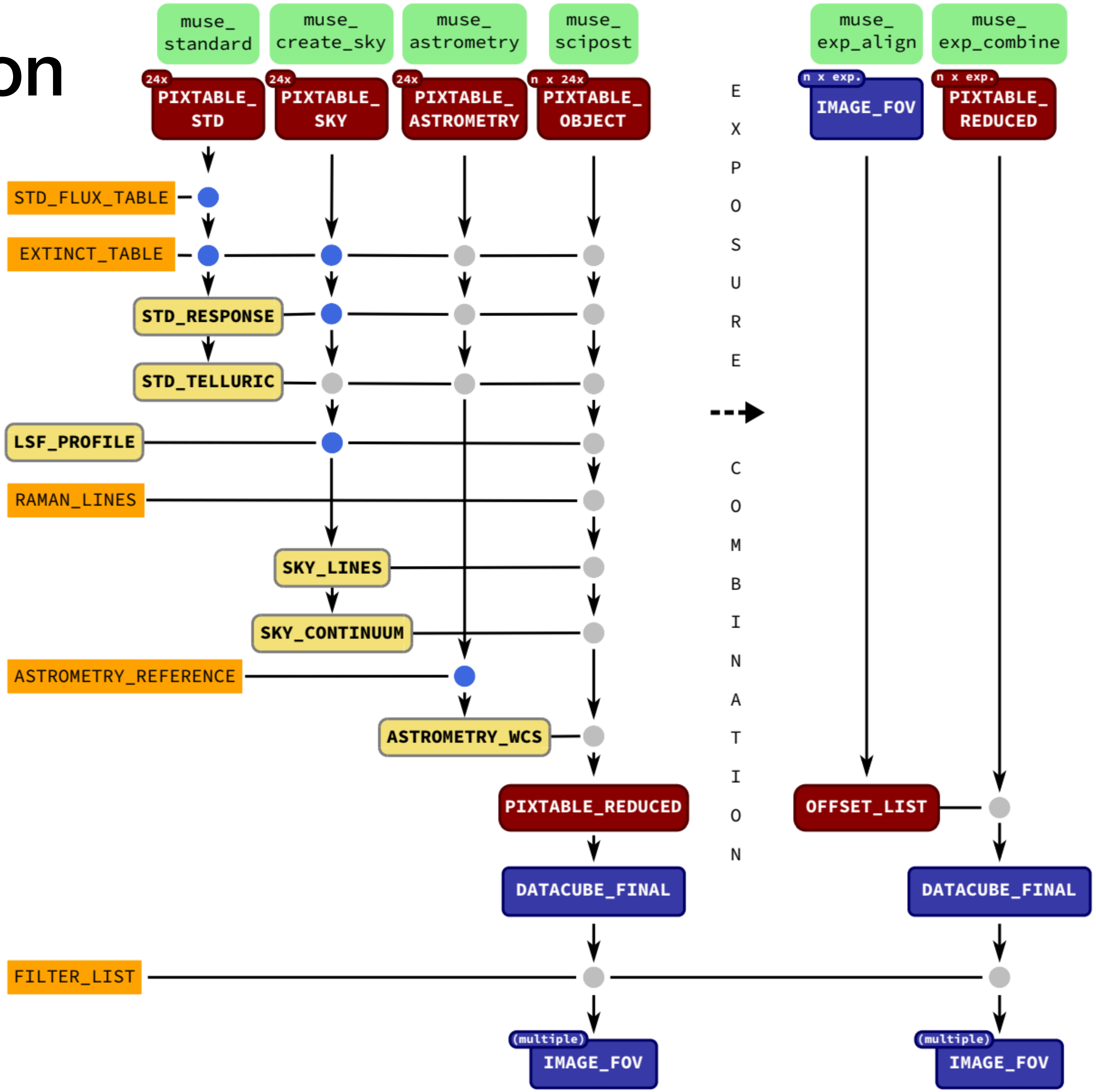
Applied to cube

MUSE Data Reduction

Post-processing

- Post-processing steps
  - muse_standard
  - muse_create_sky
  - muse_astrometry
  - muse_scipost
  - muse_align
  - muse_combine

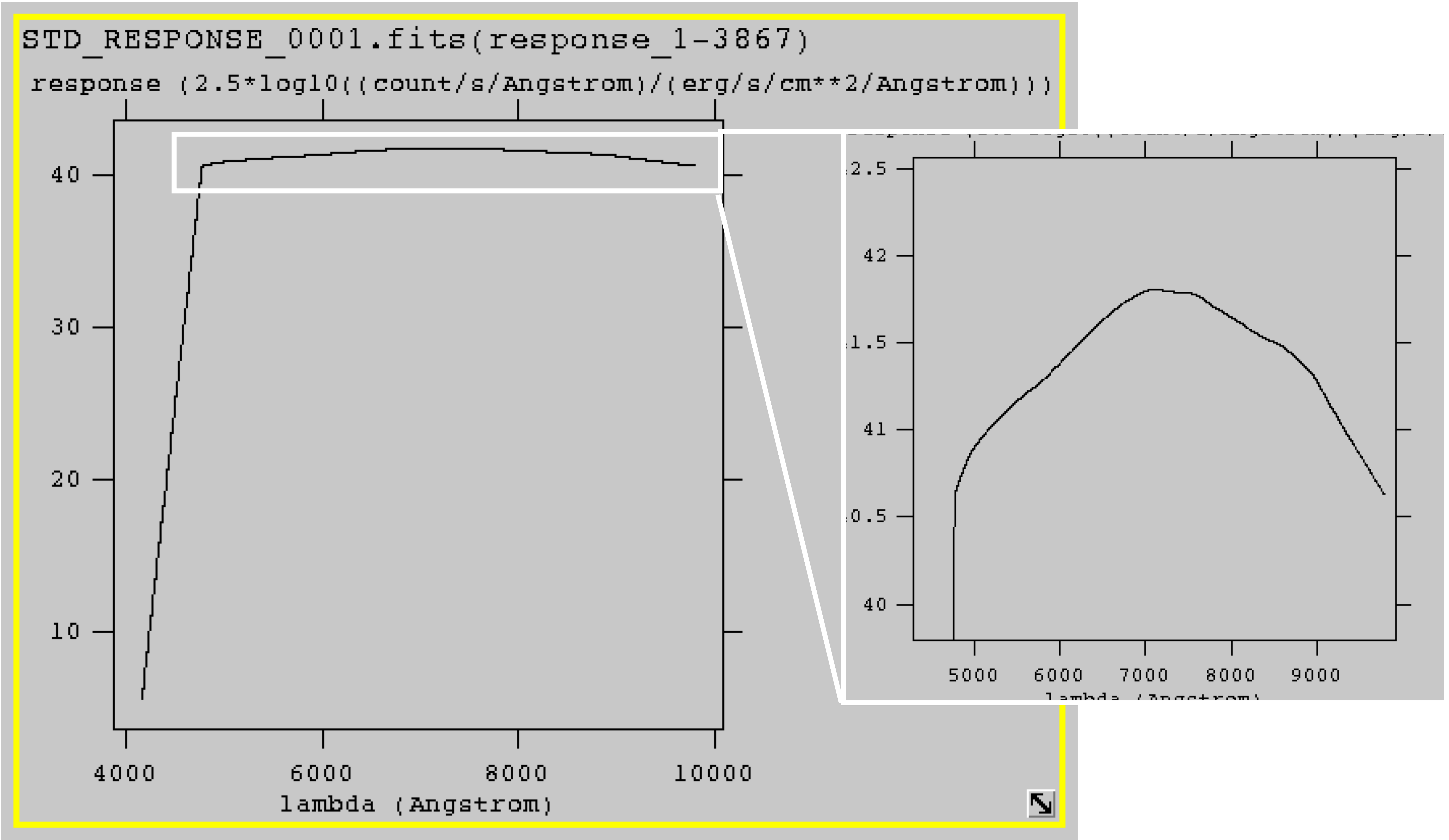




MUSE Data Reduction

muse_standard

- Measures the light from a standard star as a function of wavelength, and compares the result to a catalogue of the true flux to convert counts to photons
  ➡ **Flux calibration**
- Standard star calibration is taken each night under clear conditions, and is only applicable to that nights observations

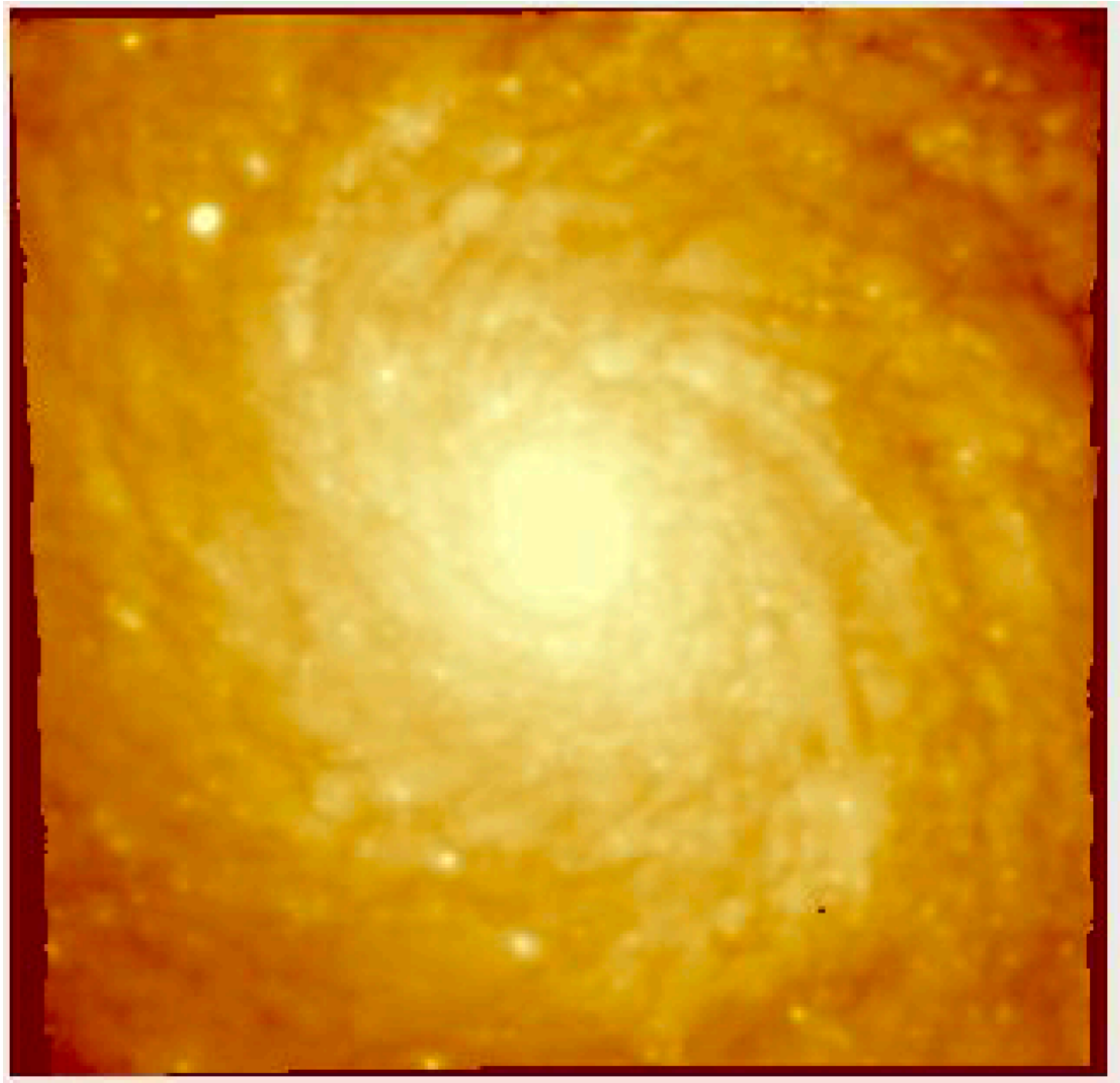


MUSE Data Reduction

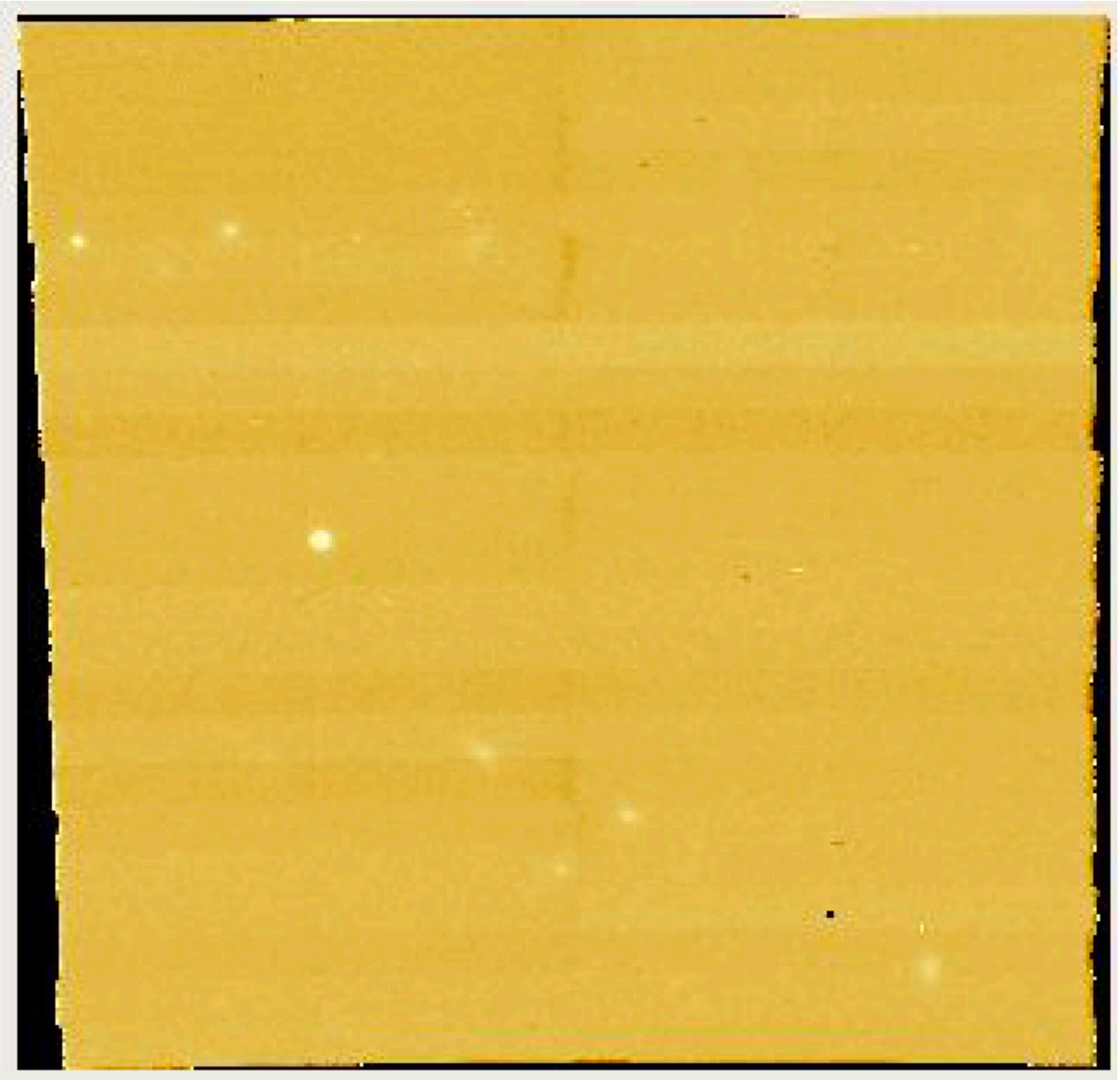
muse_create_sky

- Used **only** when the target covers most of the FOV and there is a dedicated sky exposure
- Creates the **sky_mask** and measures the sky continuum and emission lines across the datacube

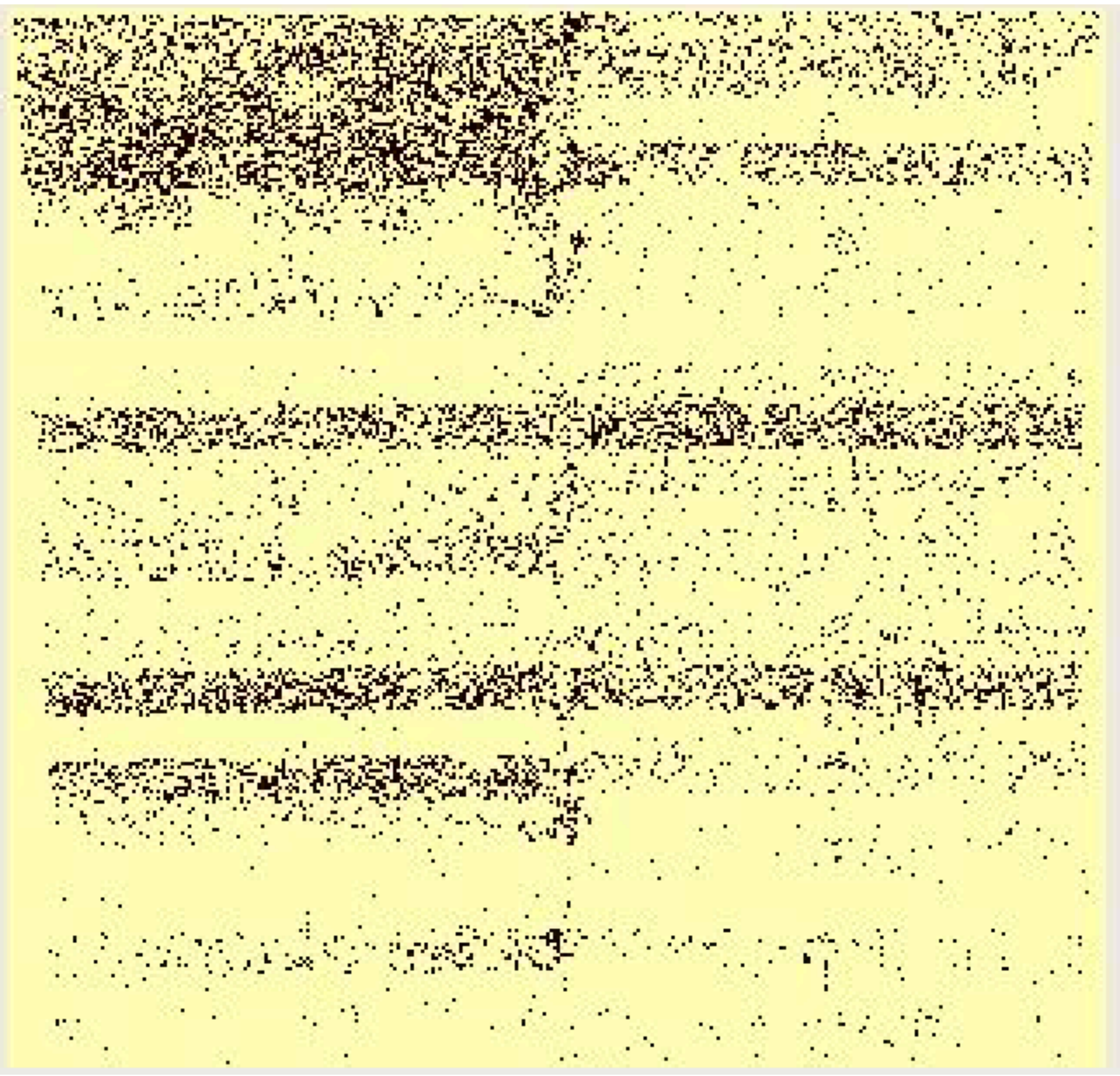
Target



Sky image



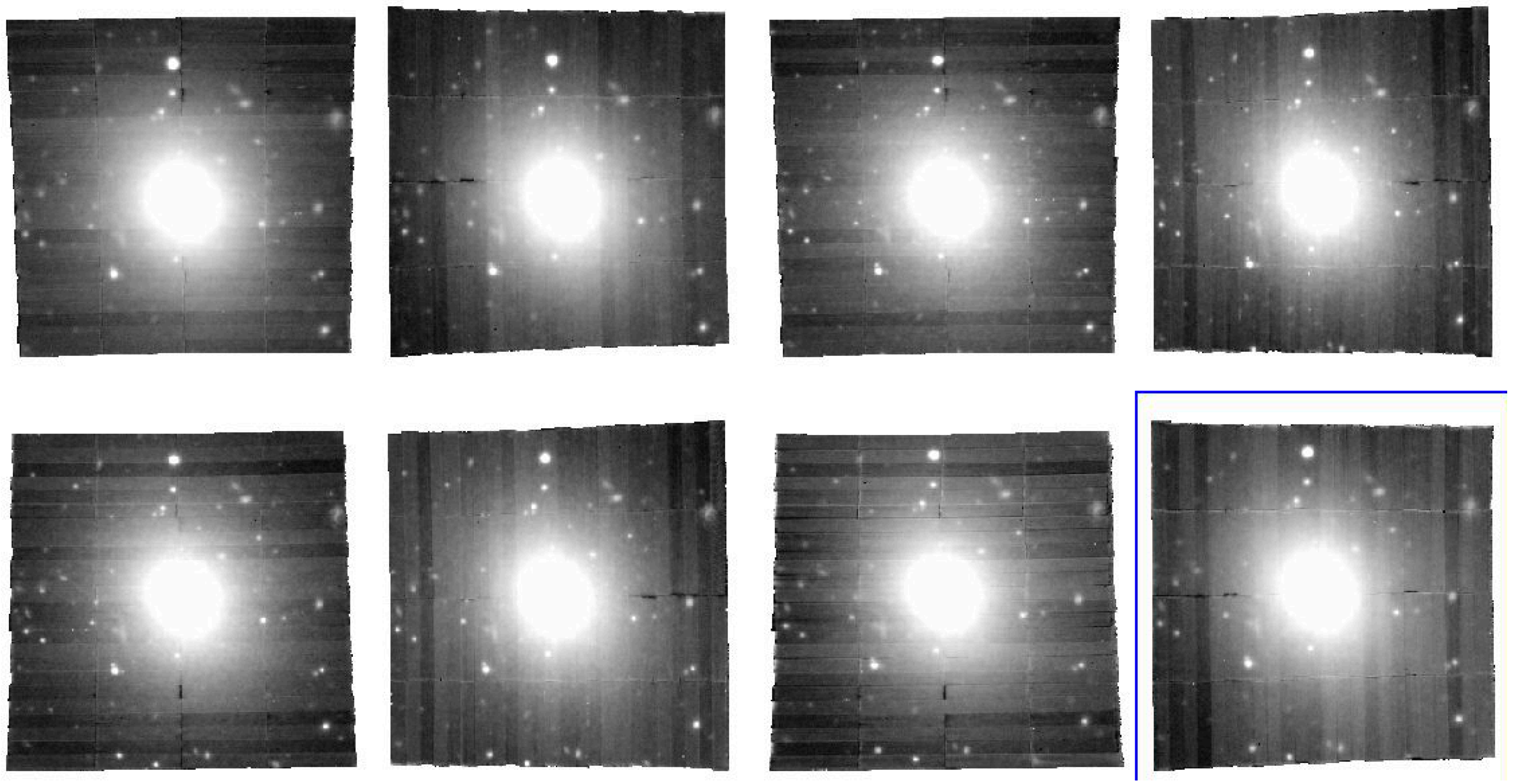
Sky mask

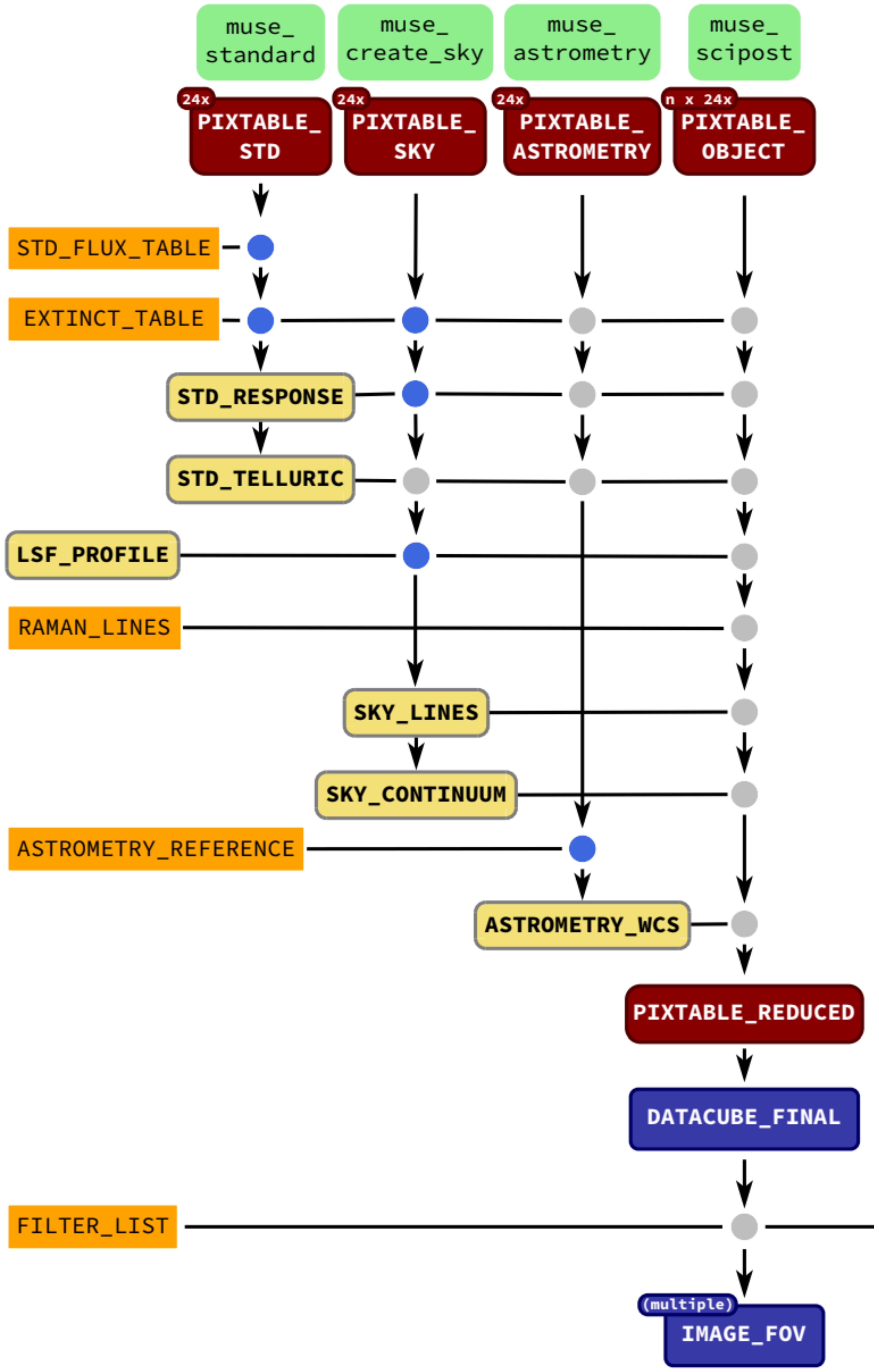


MUSE Data Reduction

muse_scipost

- Applies flux calibration, sky subtraction, and astrometry solution
- Converts pixel tables into data cubes for each exposure
- **One exposure at a time**

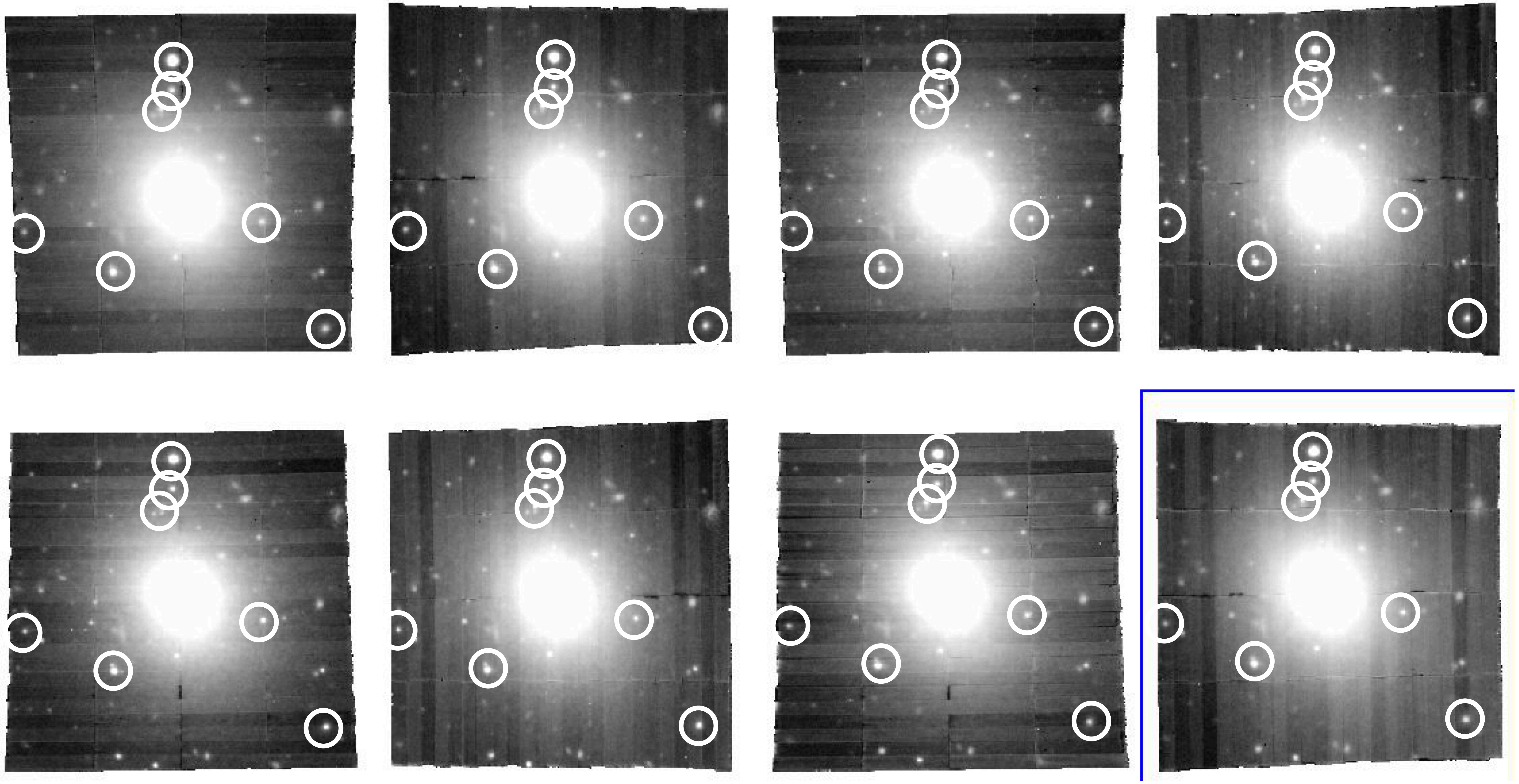




MUSE Data Reduction

muse_align

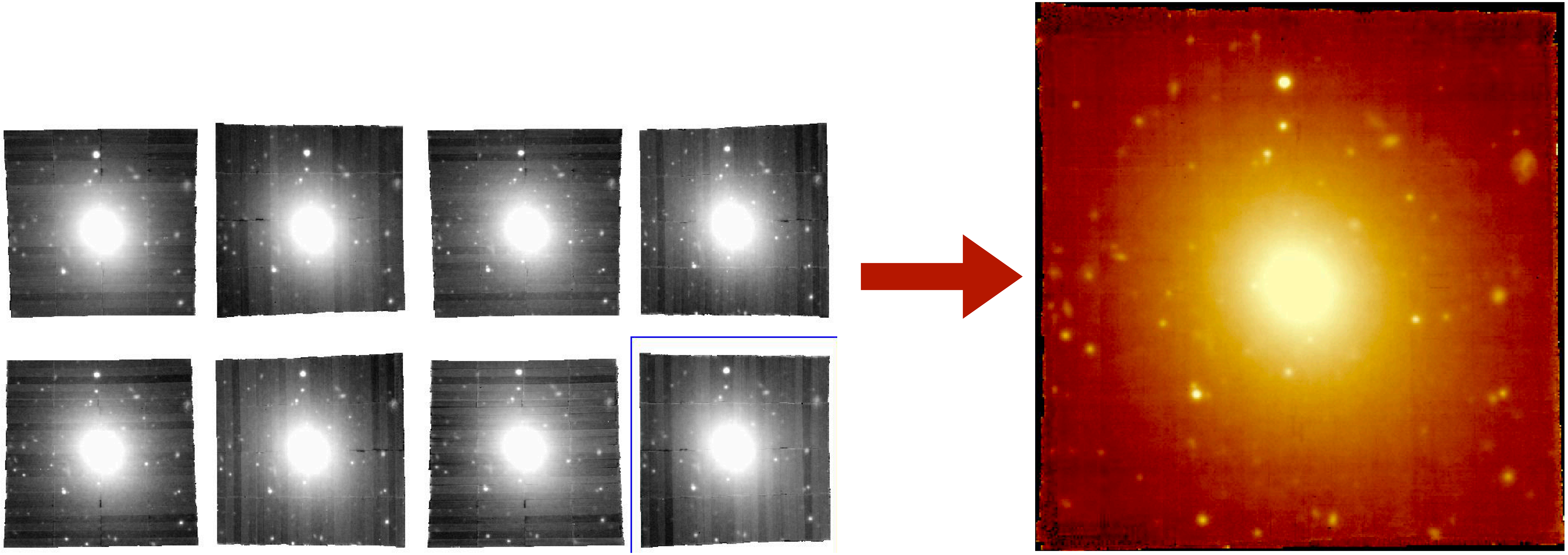
- Identifies point sources in each exposure and matches them
- Identifies the offsets required to align the images to stack them



MUSE Data Reduction

muse_combine

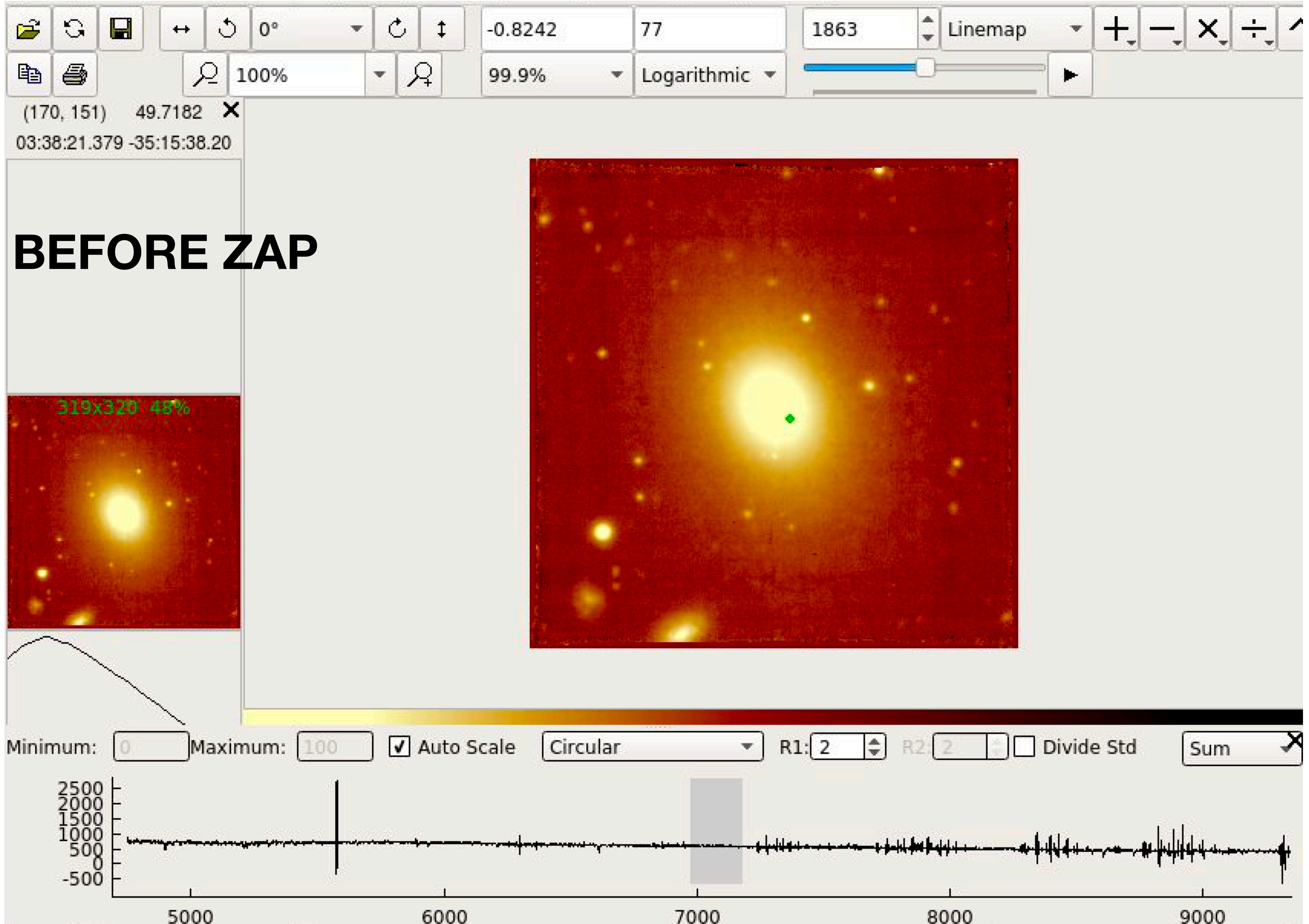
- Uses the offsets from muse_exp_align to stack the exposures
- You can alternatively use the was information, especially when creating a mosaic with very little overlap between exposures

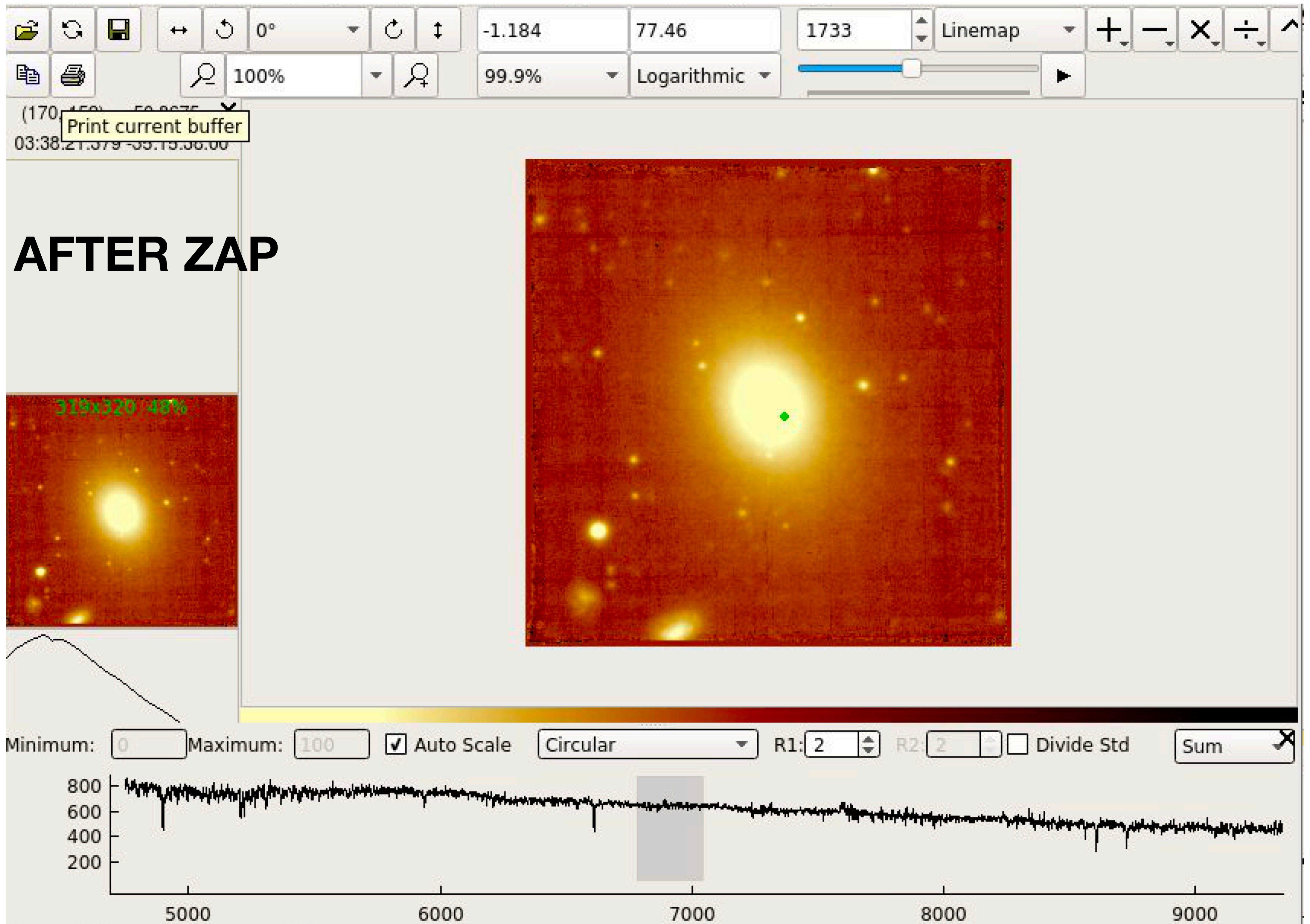


MUSE Data Reduction

ZAP: Zurich Atmospheric Purge code

- Third party software developed to apply an additional sky subtraction to the datacube
- Should be applied to each individual exposure, but achieves the same effect to within 1-2% when applies to the final datacube
- Python code- parallelised to use **every core** available on the machine
    - Please use the *nice* command when running on a shared machine (e.g. nice python)





MUSE Data Reduction

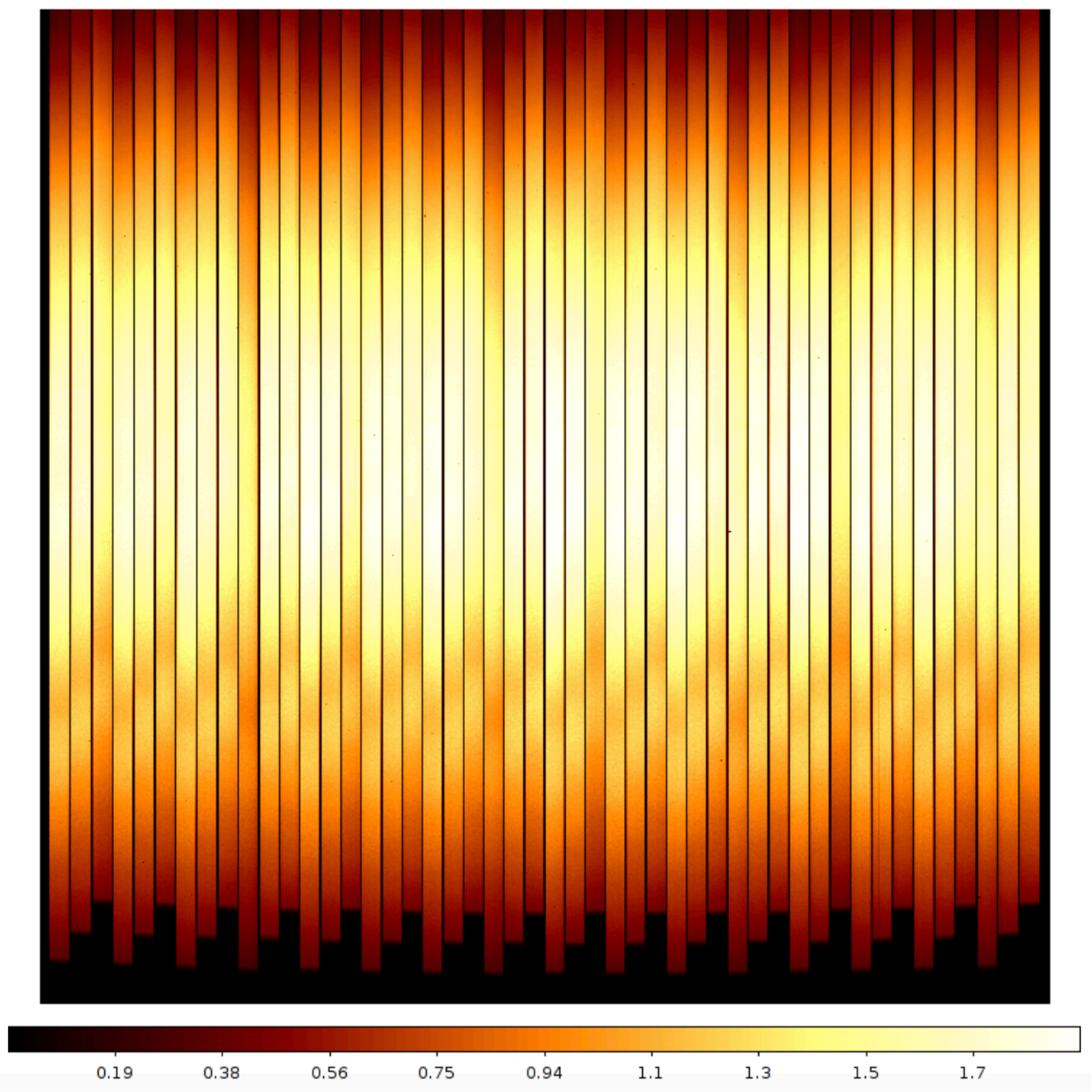
Static calibrations

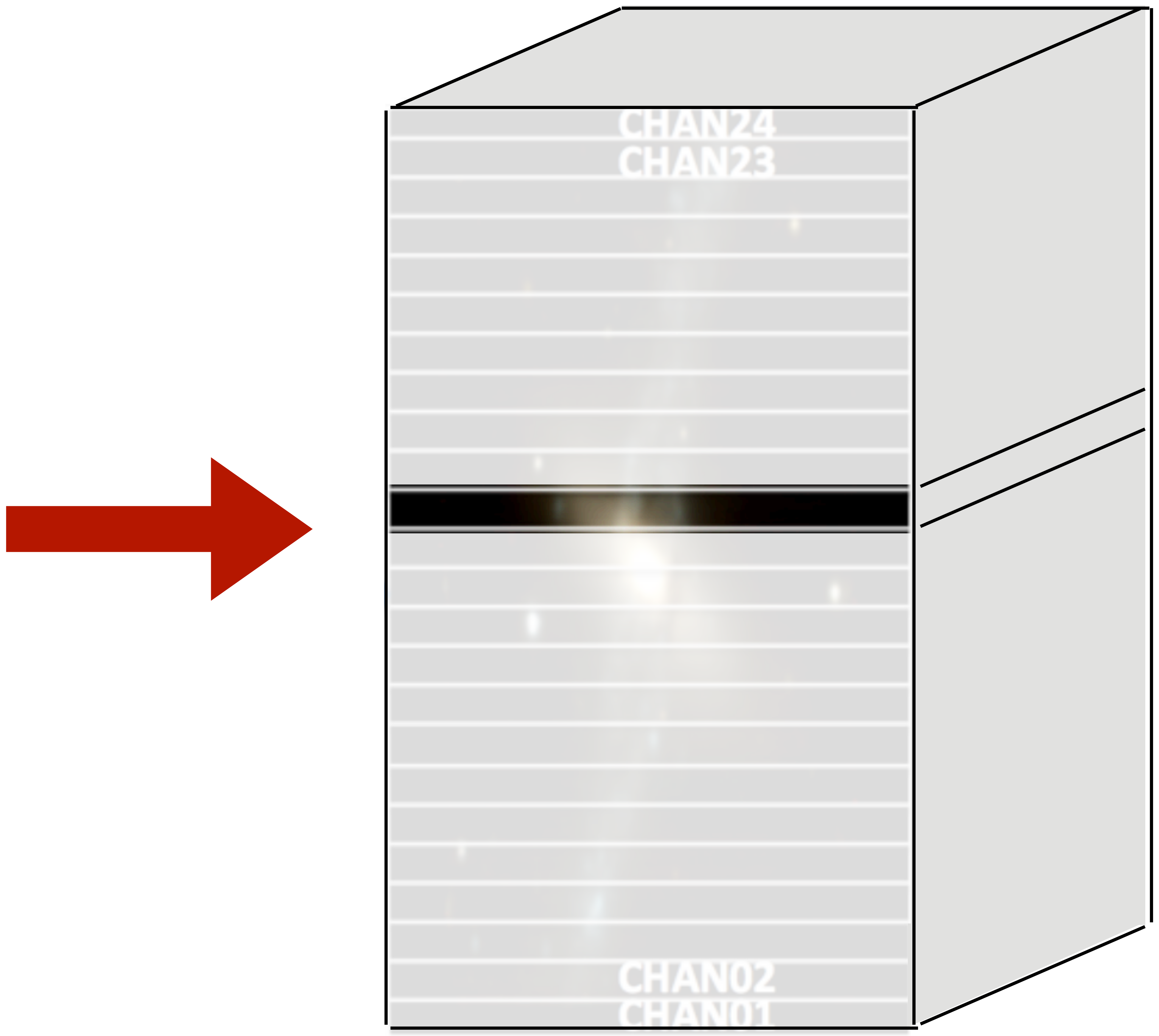
- **Bad Pixel Mask**: lists the bad pixels for each CCD
- **Extinction Table**: a measure of atmospheric extinction at Paranal as a function of wavelength
- **Filter List**: list of filter transmission curves
- **Line Catalog**: list of known positions of arc lines
- **Sky Lines Catalog**: list of known position sof sky lines
- **Standard Flux Table**: spectrum of the spectroscopic standard star
- **Vignetting Mask**: mask to correct for vignetting in lower right corner of FOV- only for data observed before 10th March 2017

MUSE Data Reduction

Static calibrations

- **Geometry Table**: uses the trace table to identify where in the datacube each pixel in each CCD lies

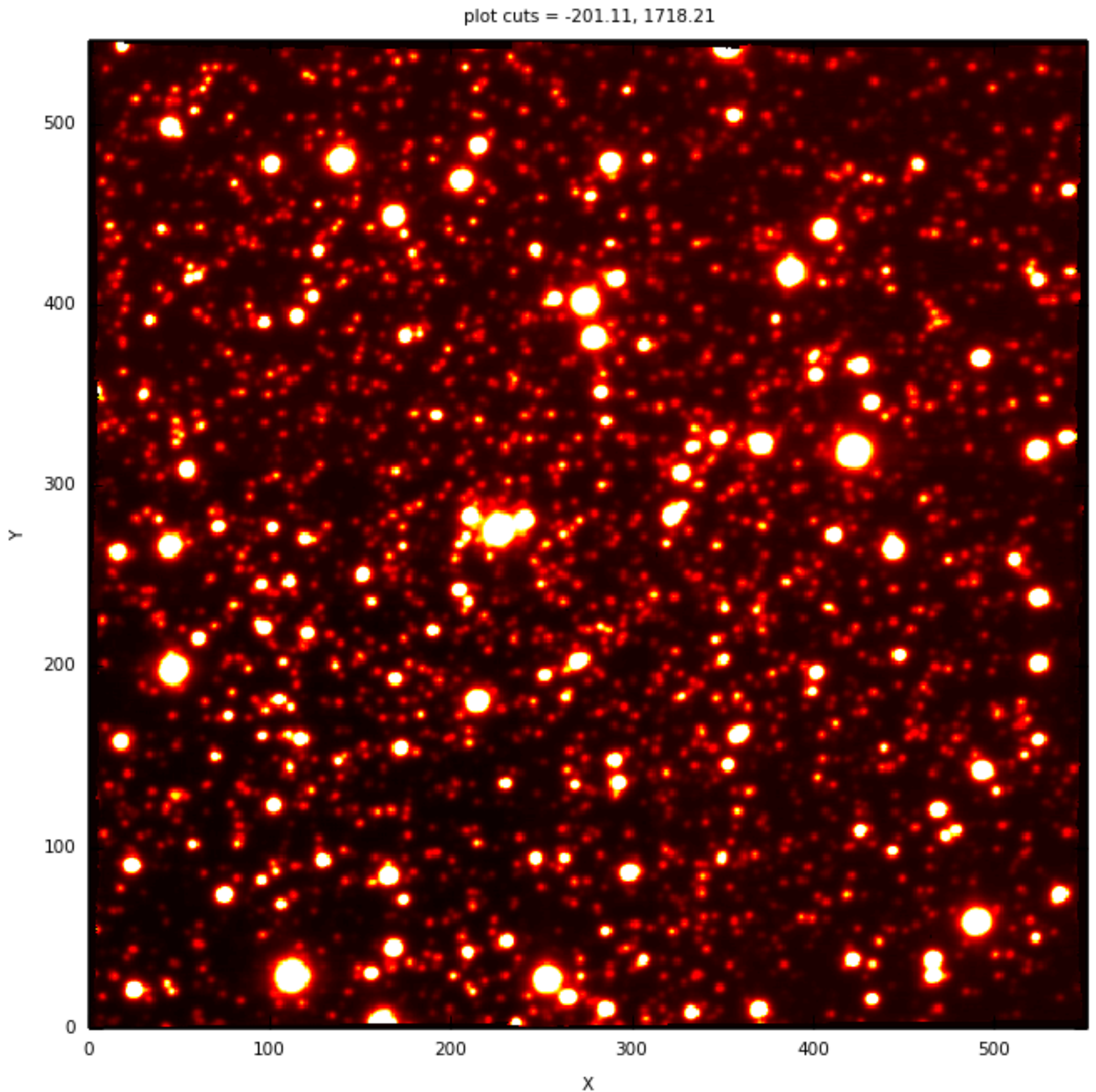


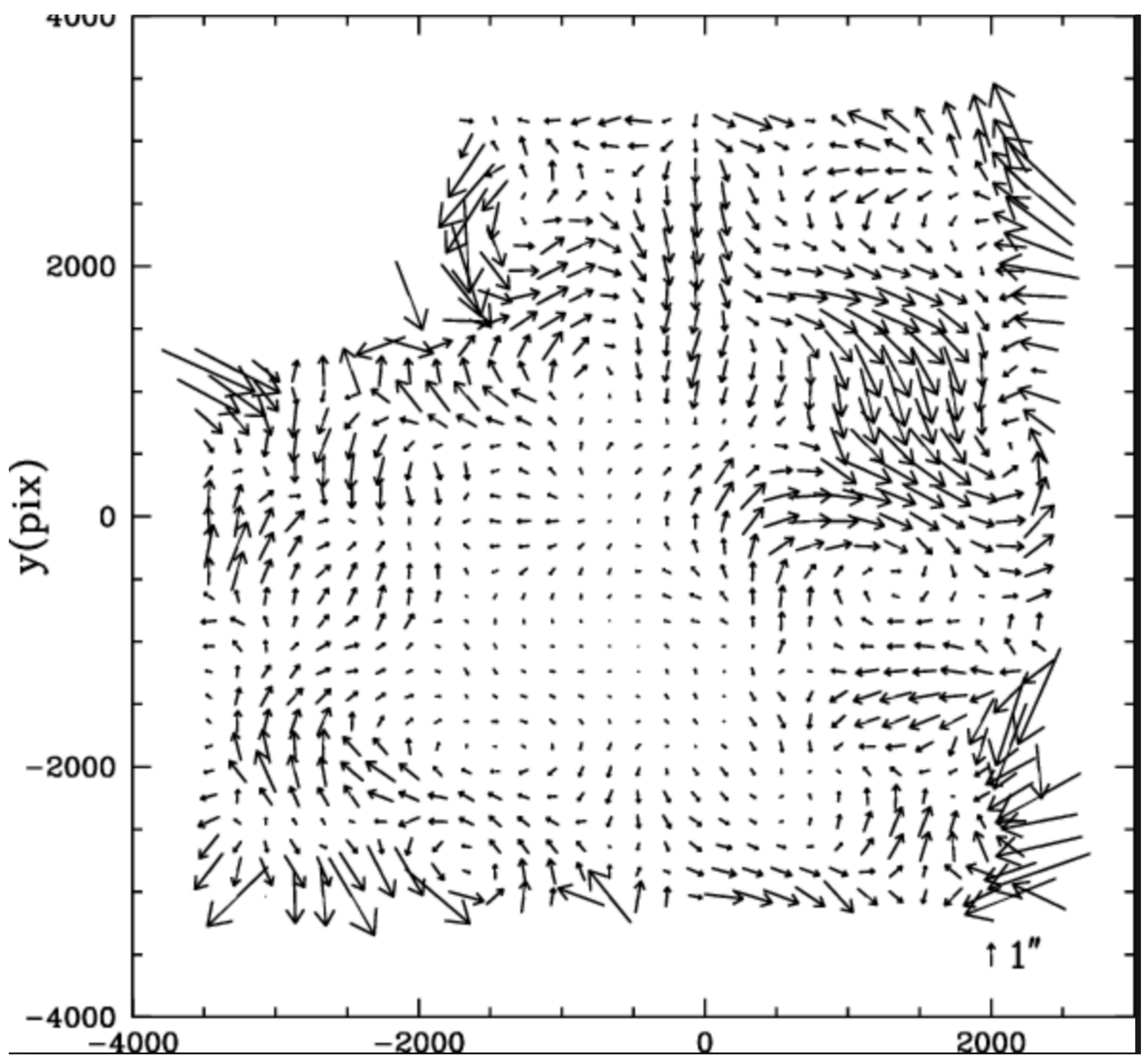


MUSE Data Reduction

Static calibrations

- **Astrometry WCS**: takes an exposure of a star cluster, identifies point sources, and compares the locations with coordinates of known stars to measure offsets across FOV. Also measures the PSF across the field





Position offsets for INT/WFC, Garcia et al (2009)

Troubleshooting

Common issues when reducing MUSE data

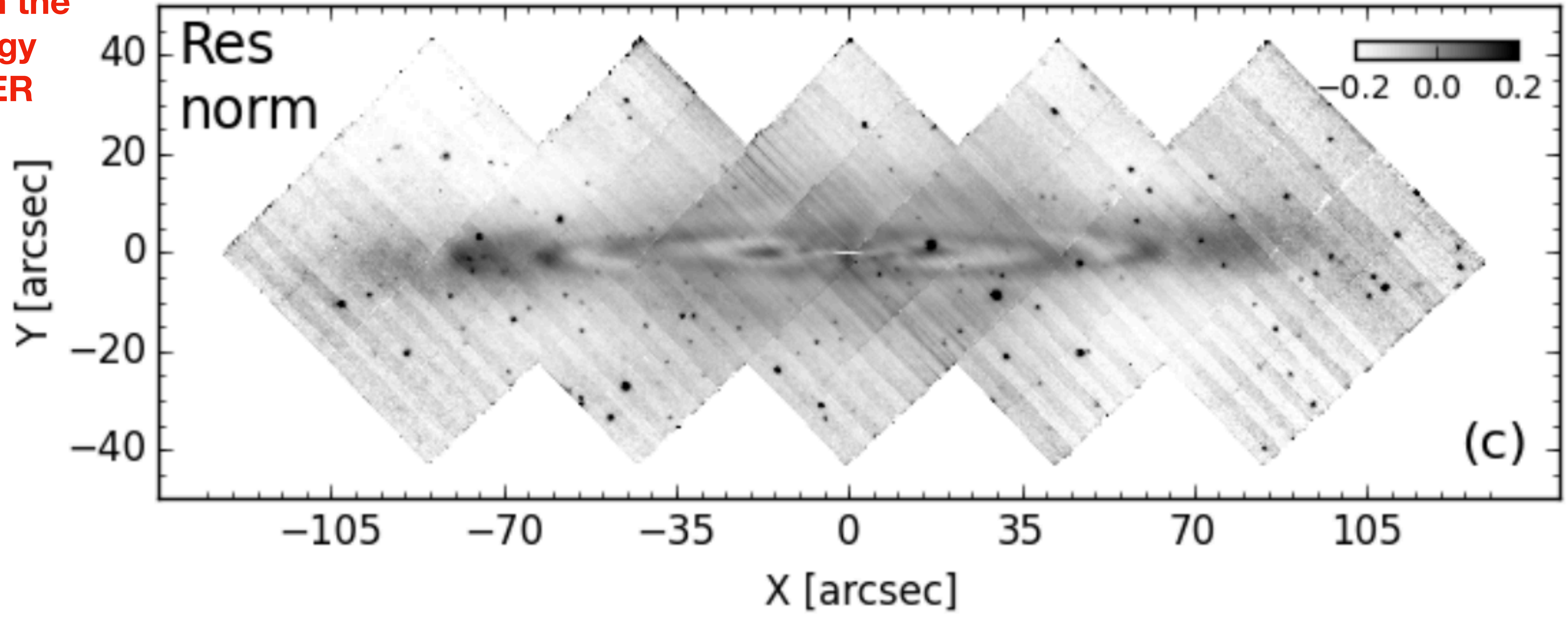
ESO Data Reduction Pipelines

Common issues when reducing MUSE data

No offsets or rotations between exposures

By rotating and dithering between each exposure, you can reduce the appearance of the slicers and channels in the final datacube. This strategy was only determined AFTER science verification.

NGC 3115



Guereou et al (2016)

ESO Data Reduction Pipelines

Common issues when reducing MUSE data

<u>**No illumination calibration**</u>

The background level in each detector is temperature dependant and time varying.

The illumination flat is taken every hour or when there has been a significant temperature change to measure the differences in background level between each IFU.

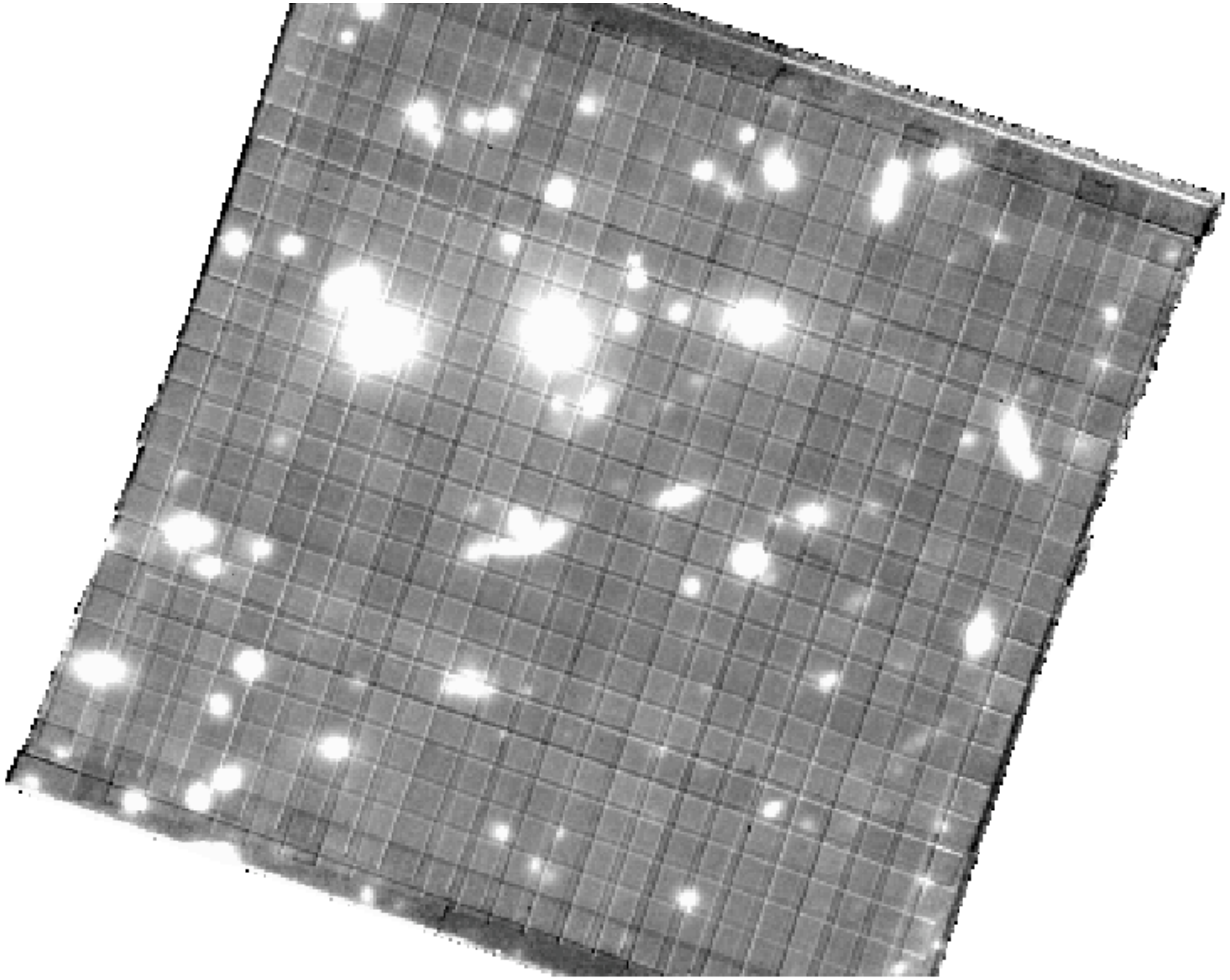


Image credit: Felipe Barrientos

ESO Data Reduction Pipelines

Common issues when reducing MUSE data

<u>No bad pixel mask</u>
ESO Reflex doesn't always see and use the bad pixel mask, leading to lots of artefacts in the final datacube

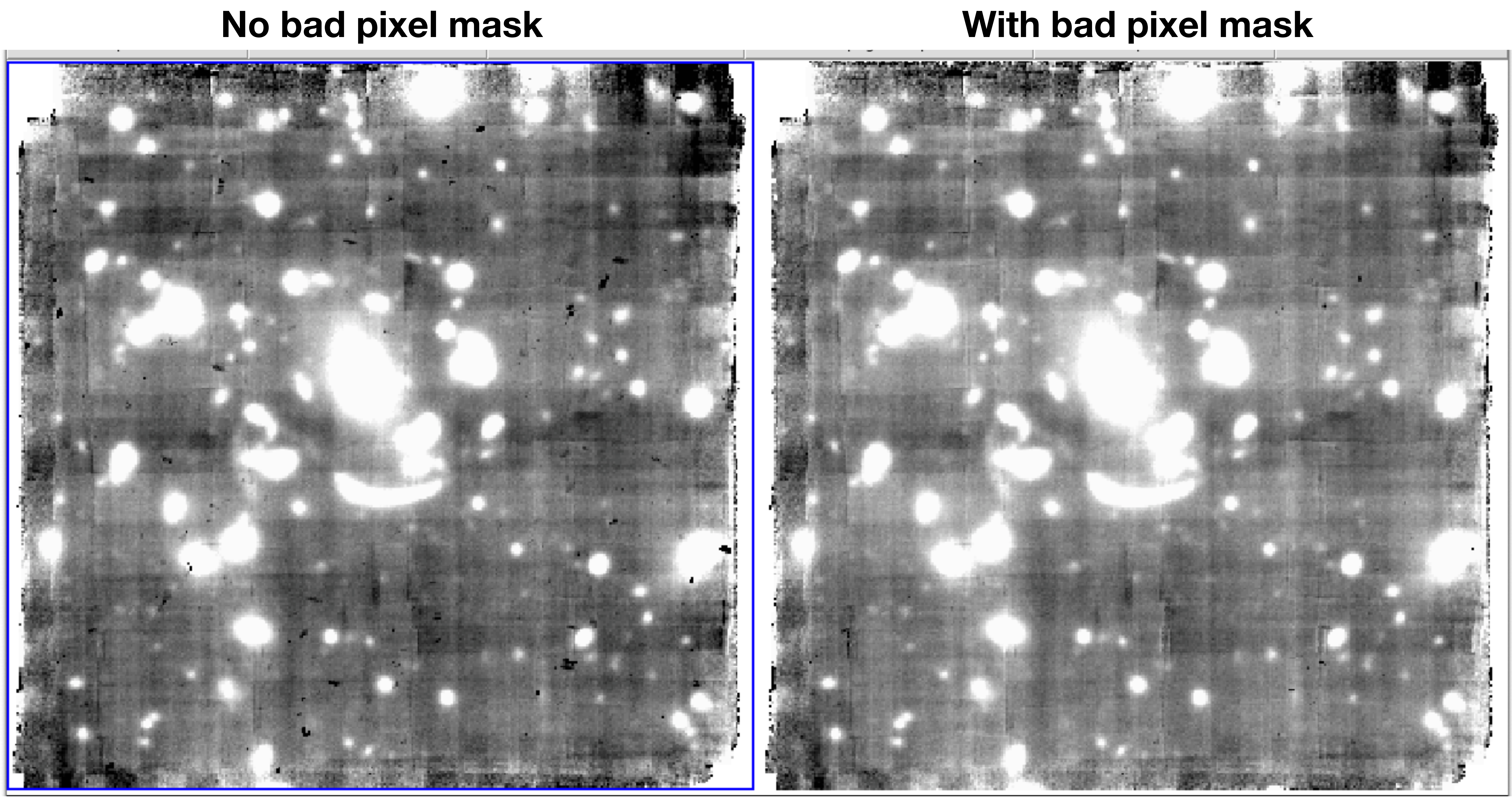


Image credit: Felipe Barrientos

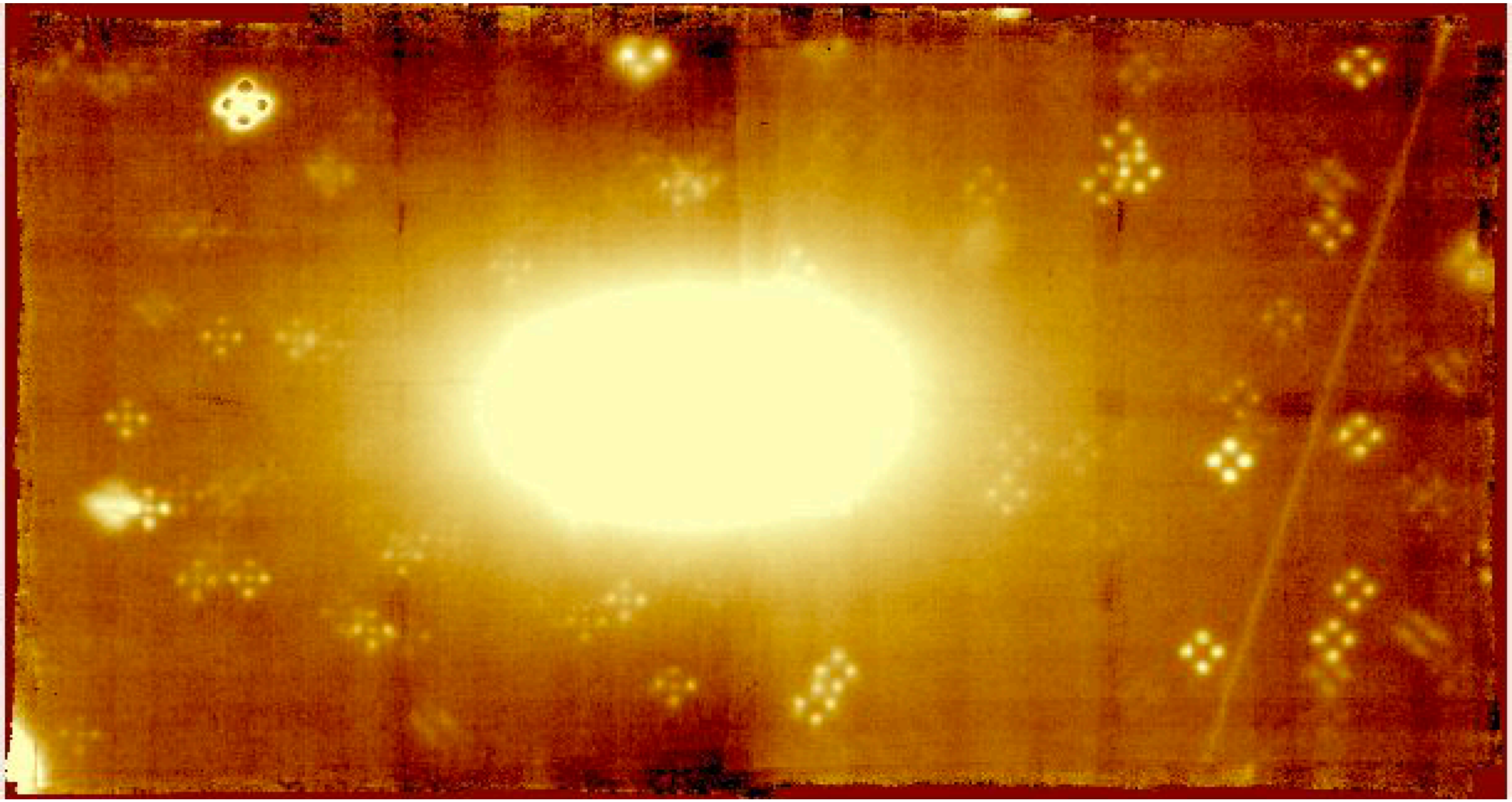
ESO Data Reduction Pipelines

Common issues when reducing MUSE data

<u>Offset list issues</u>

If there is very little overlap in the esposures, muse_exp_align can have issues finding enough stars to match for the alignment.

Note: In this example I also omitted the first channel in the scipost step, throwing off the WCS.

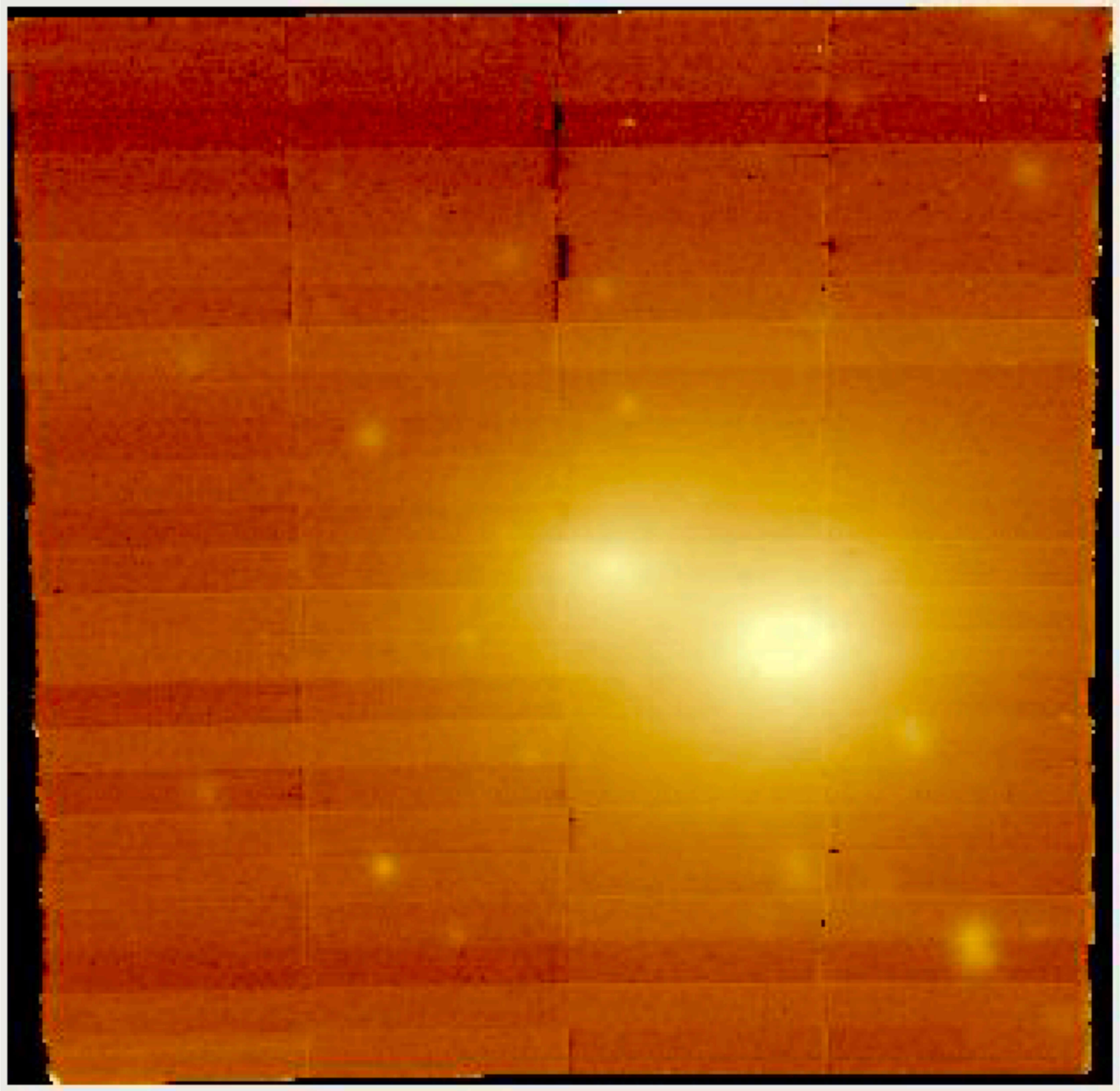


ESO Data Reduction Pipelines

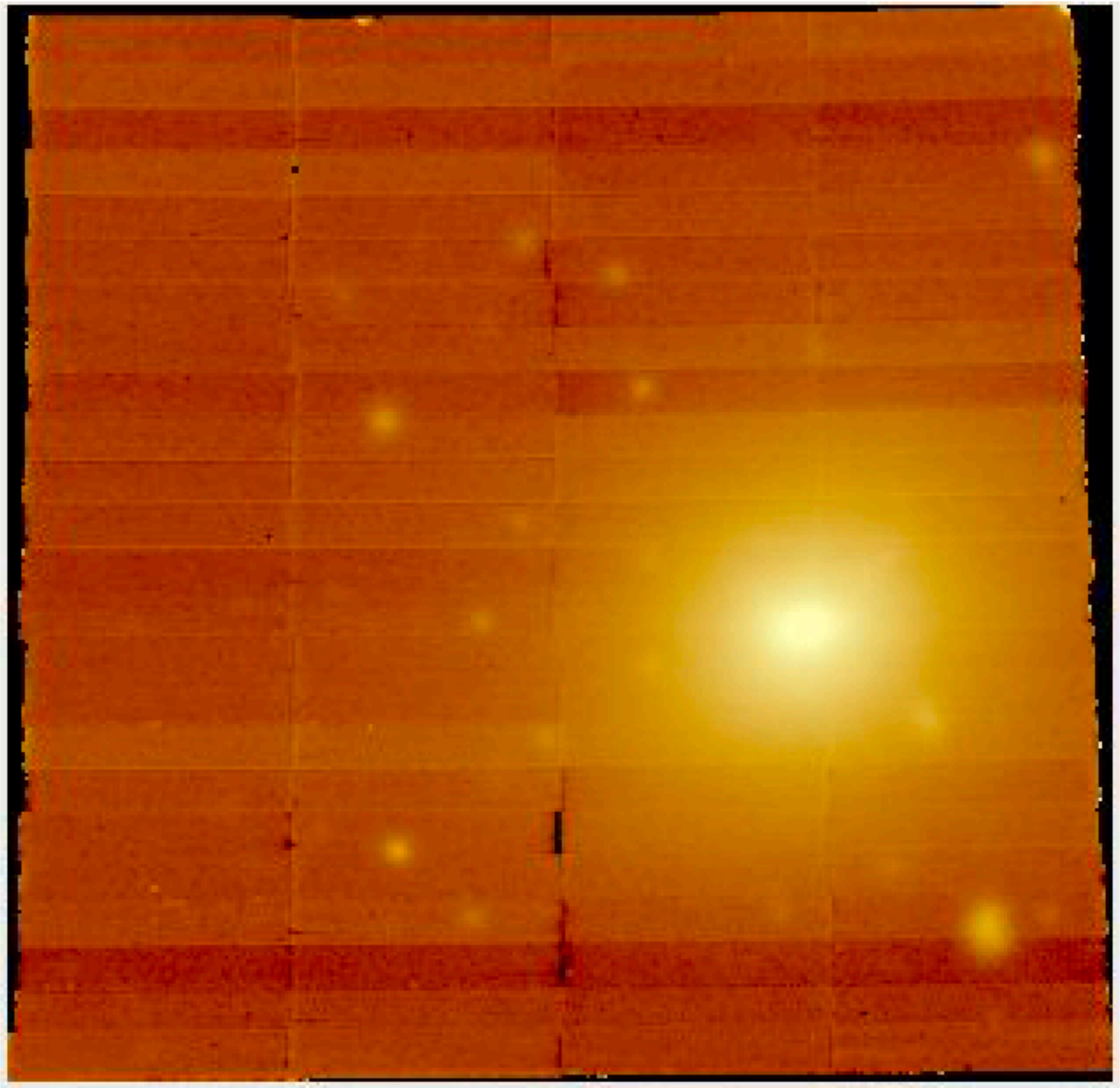
Common issues when reducing MUSE data

<u>Telescope jumps</u>
Occasionally, the telescope might jump or lose the tracking. This most often happens when there are thick clouds that obscure the guide star.

Telescope jumps



Telescope maintains the guiding

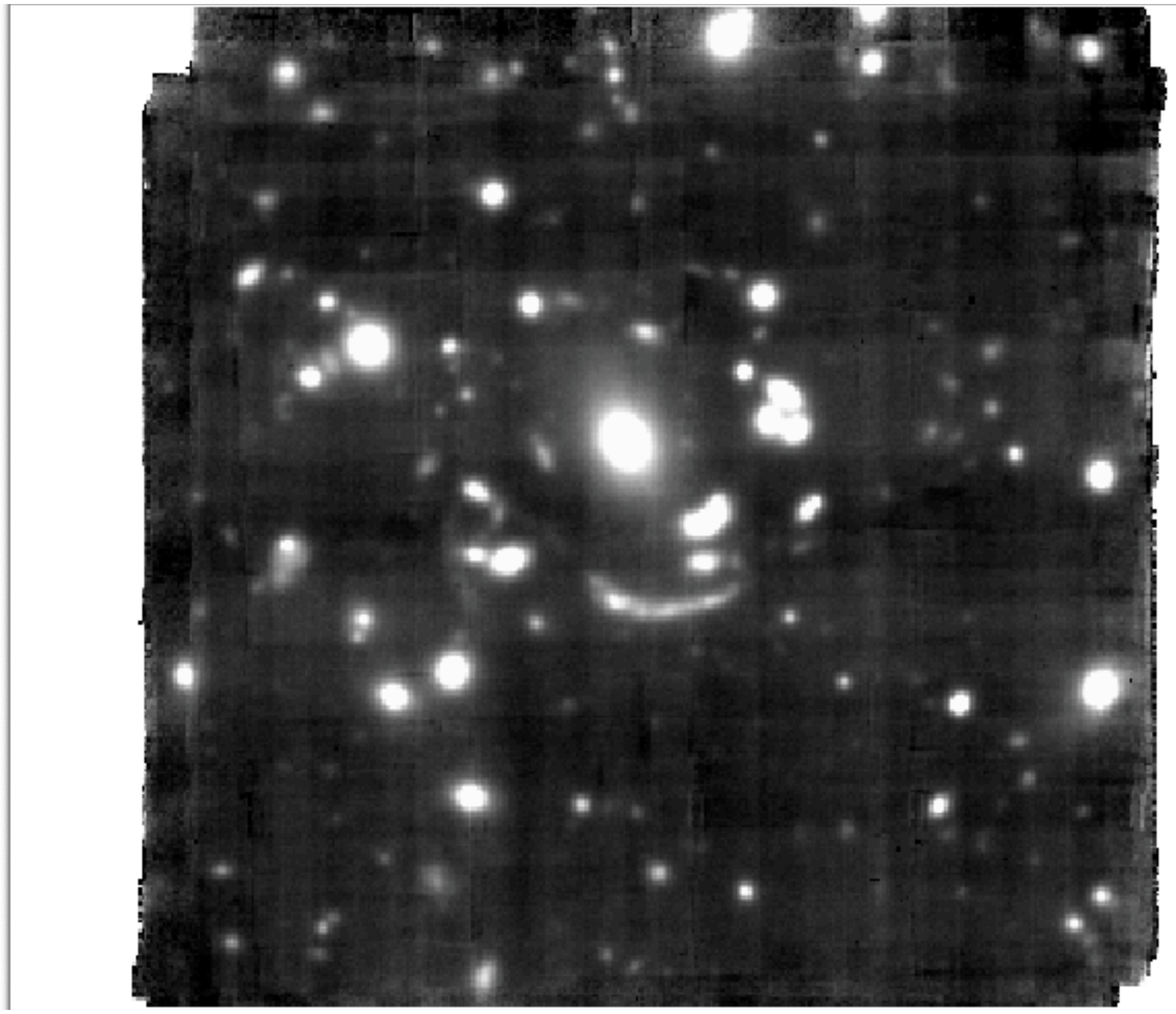


ESO Data Reduction Pipelines

Common issues when reducing MUSE data

<u>No offset list provided</u>
pipeline stacks images using simply the WCS information

With offset list



No offset list

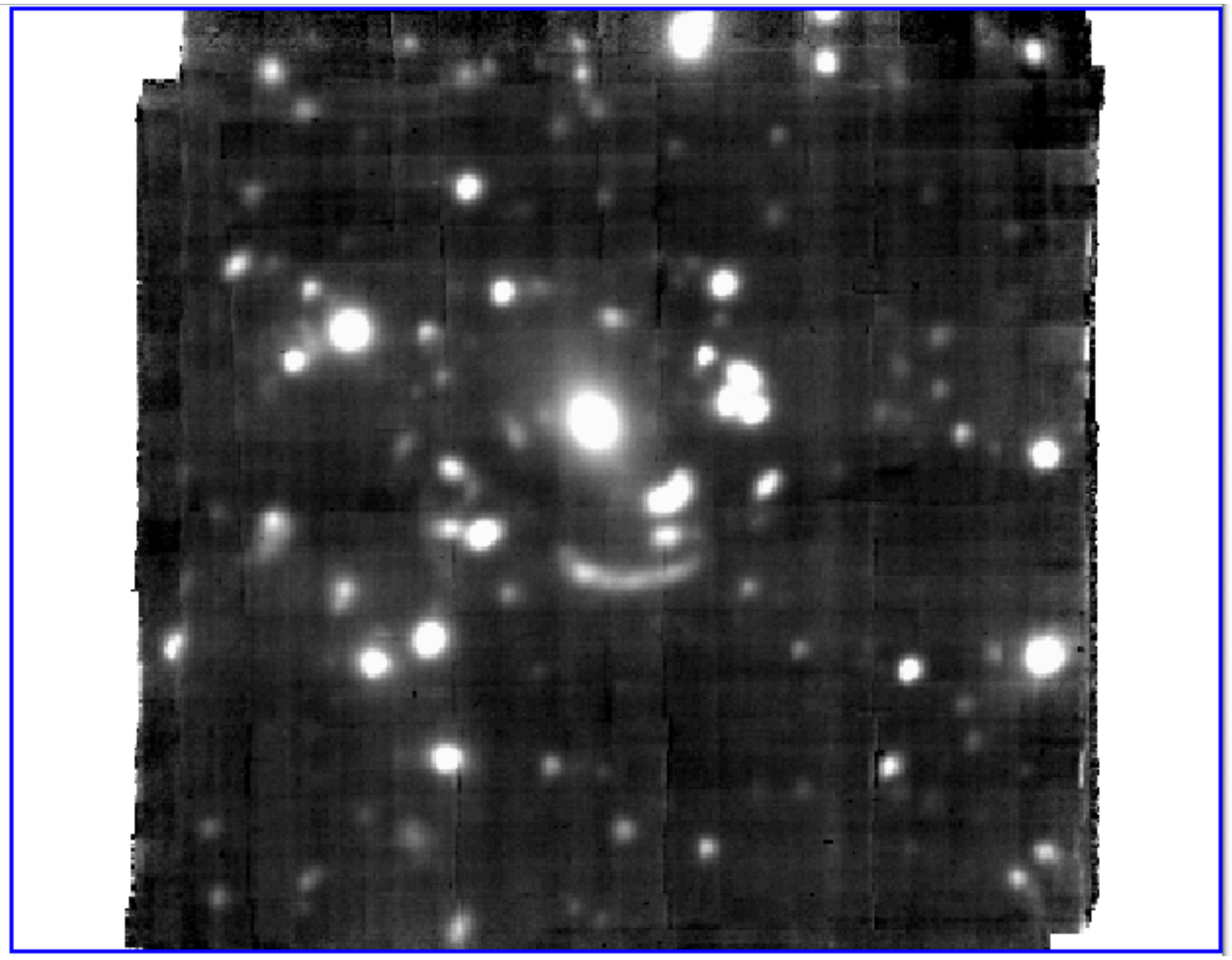


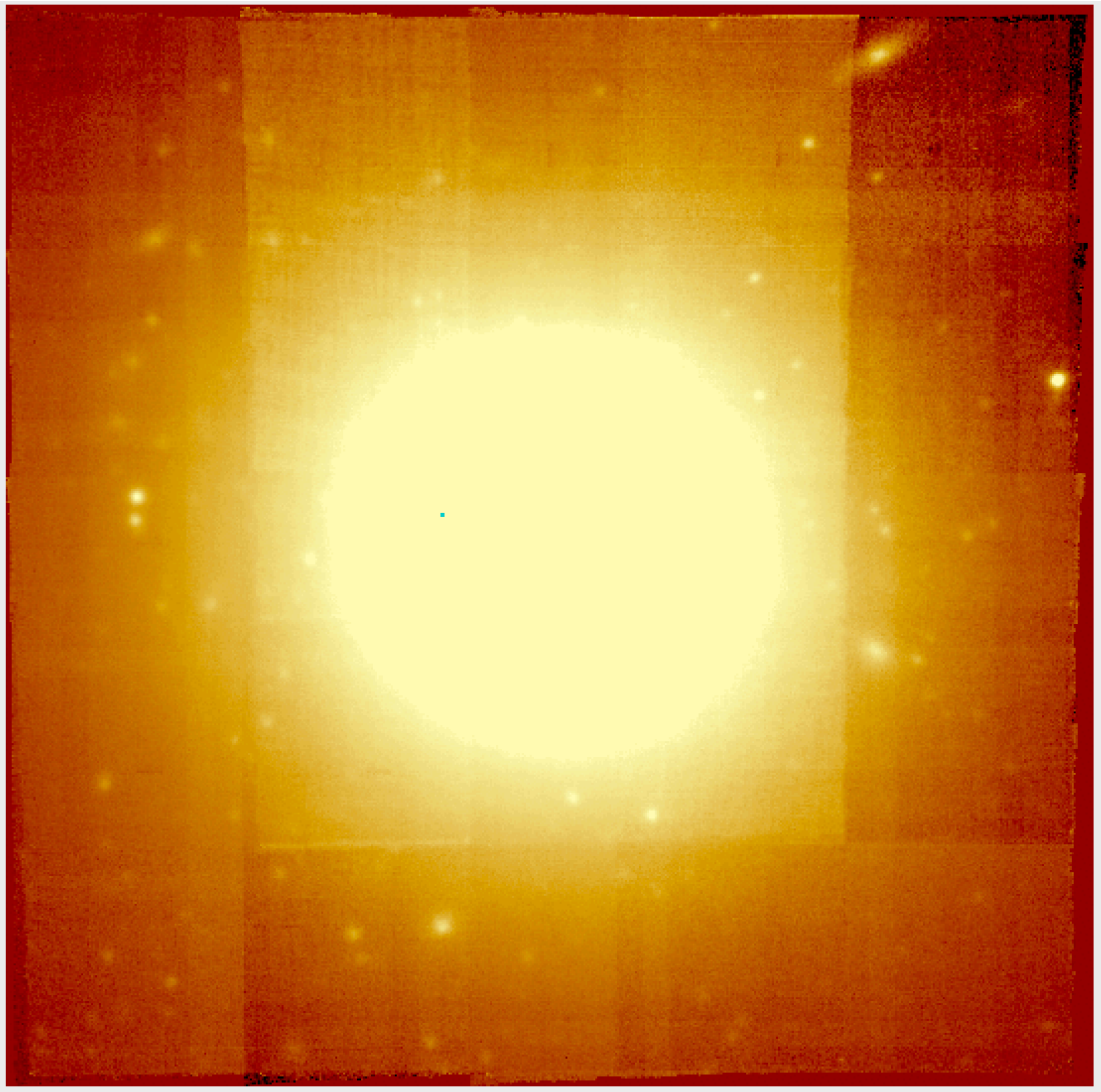
Image credit: Felipe Barrientos

ESO Data Reduction Pipelines

Common issues when reducing MUSE data

Not enough/no sky exposures

This datacube consists of 9 exposures, observed in 2 blocks with one sky exposure per block. Both data sets were observed through fast-moving, thin clouds, leading to different background levels



OK, you've got my attention…

How can I access MUSE data?

How to Access MUSE data?

- Apply for time
  - Calls for proposals twice a year, in March and September

- Look in the ESO Archive Facility
  - Observations since 2014
  - All data is proprietary initially, but becomes publicly available after one year
  - Good practice to contact the PI if you are planning to use their data from the archive
  - Best to download and reduce the raw data. Reduced data is available as phase III products, but I find these are of inconsistent quality.

How to Access MUSE data?

Observation classification

- A night log is completed each night, and provided along with any data you download.
- The log contains information on weather, instrument set-up, comments from the night astronomer, and OB classification:
    - **A:** observed completely within constraints set by PI
    - **B:** constraints violated by <10%. See comment from night astronomer
    - **C:** constraints violated by >10%. OB re-entered into the queue to be observed again
    - **D:** constraints violated by >10%, but OB will not be repeated.

MUSE DR workshops

7th August
- Julio Olivares
- Daniela Soto
- Nicholas M
- Felipe Barrientos
- Chelsea Spengler
- Thomas Puzia
- Yu Rong

9th August
- Sam Kim
- Ezequiel Treister
- Fransisco Carrasco
- Rodrigo Carvajal
- Katerine Jaochimi
- Constanza Muñoz
- Tianwen Cao

23rd August
- Javier Minniti
- Dusan Tubin
- Fabio Vito
- Julio Chaname
- Alvaro Rojas
- Demetra De Cicco
- Guiseppe D'ago

Giordano Bruno, 14:00

Please remember to download the X2go software and bring your laptop

Useful Links

- MUSE homepage
  https://www.eso.org/sci/facilities/paranal/instruments/muse/overview.html
- MUSE User Manual:
  https://www.eso.org/sci/facilities/paranal/instruments/muse/doc/ESO-261650_MUSE_User_Manual.pdf
- MUSE pipeline manual
  file:///Users/ejohnston/Downloads/muse-pipeline-manual-2.0.1.pdf
- MPDAF
  https://mpdaf.readthedocs.io/en/latest/muse.html
- ZAP
  https://zap.readthedocs.io/en/latest/
- ESO Archive
  http://archive.eso.org/eso/eso_archive_main.html