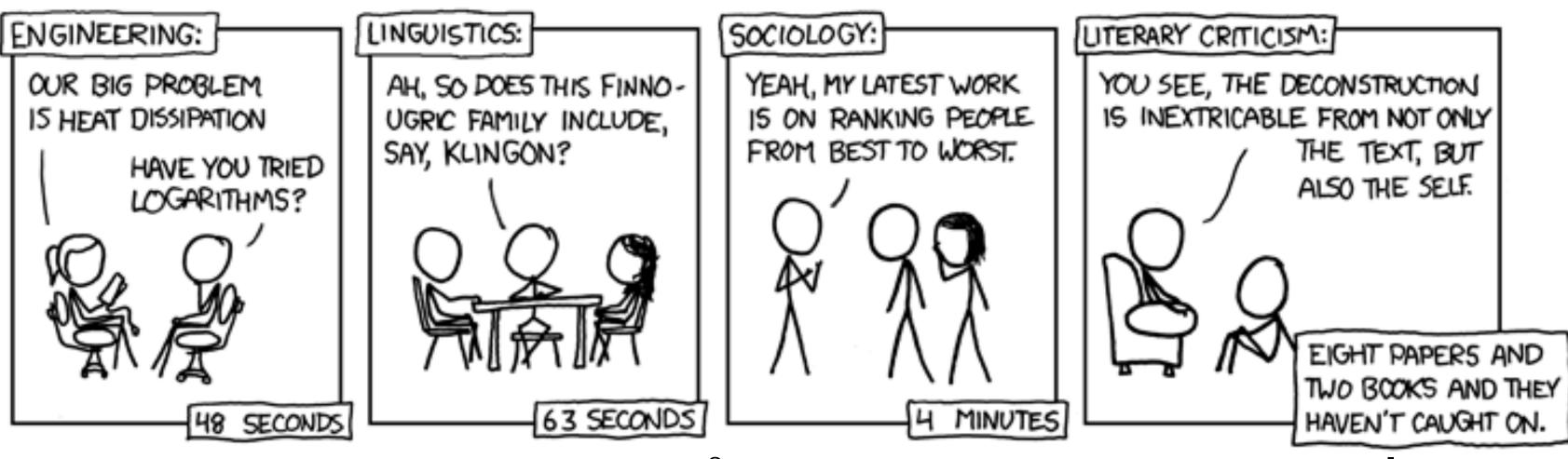
MUSE Data Reduction Workshop

Evelyn Johnston

Disclaimer: I am not a MUSE expert

am simply an experienced user of MUSE data

- I was the MUSE fellow at ESO
- I have reduced goodness knows how many MUSE datacubes lacksquare
- People keep asking me for help reducing MUSE data, and we usually manage to figure out the \bullet issue



MUSE Data Reduction Workshop, PUC, August 2019

MY HOBBY: SITTING DOWN WITH GRAD STUDENTS AND TIMING HOW LONG IT TAKES THEM TO FIGURE OUT THAT

I'M NOT ACTUALLY AN EXPERT IN THEIR FIELD.

Image credit: xkcd.com/451/

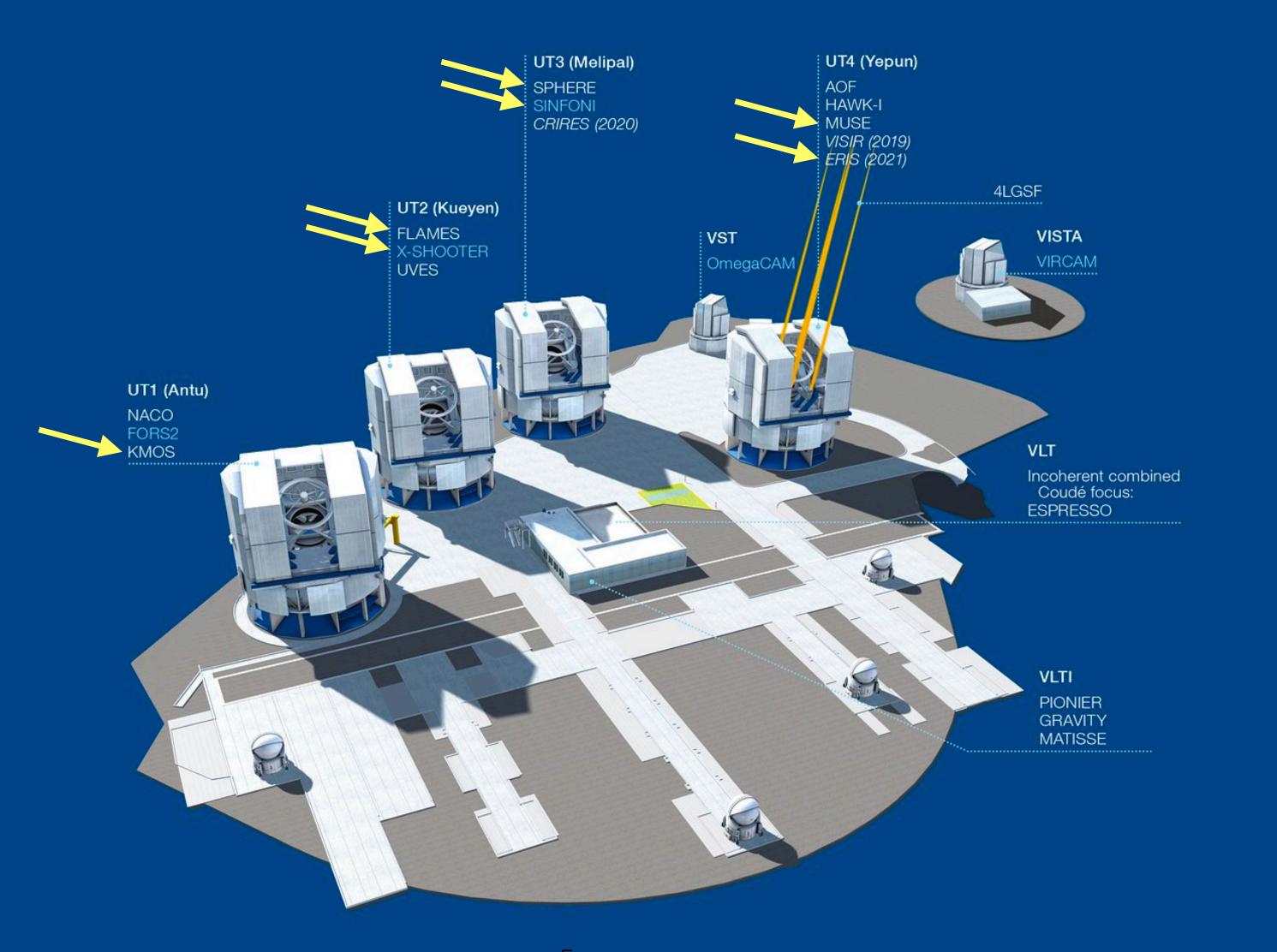


Outline

- 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?

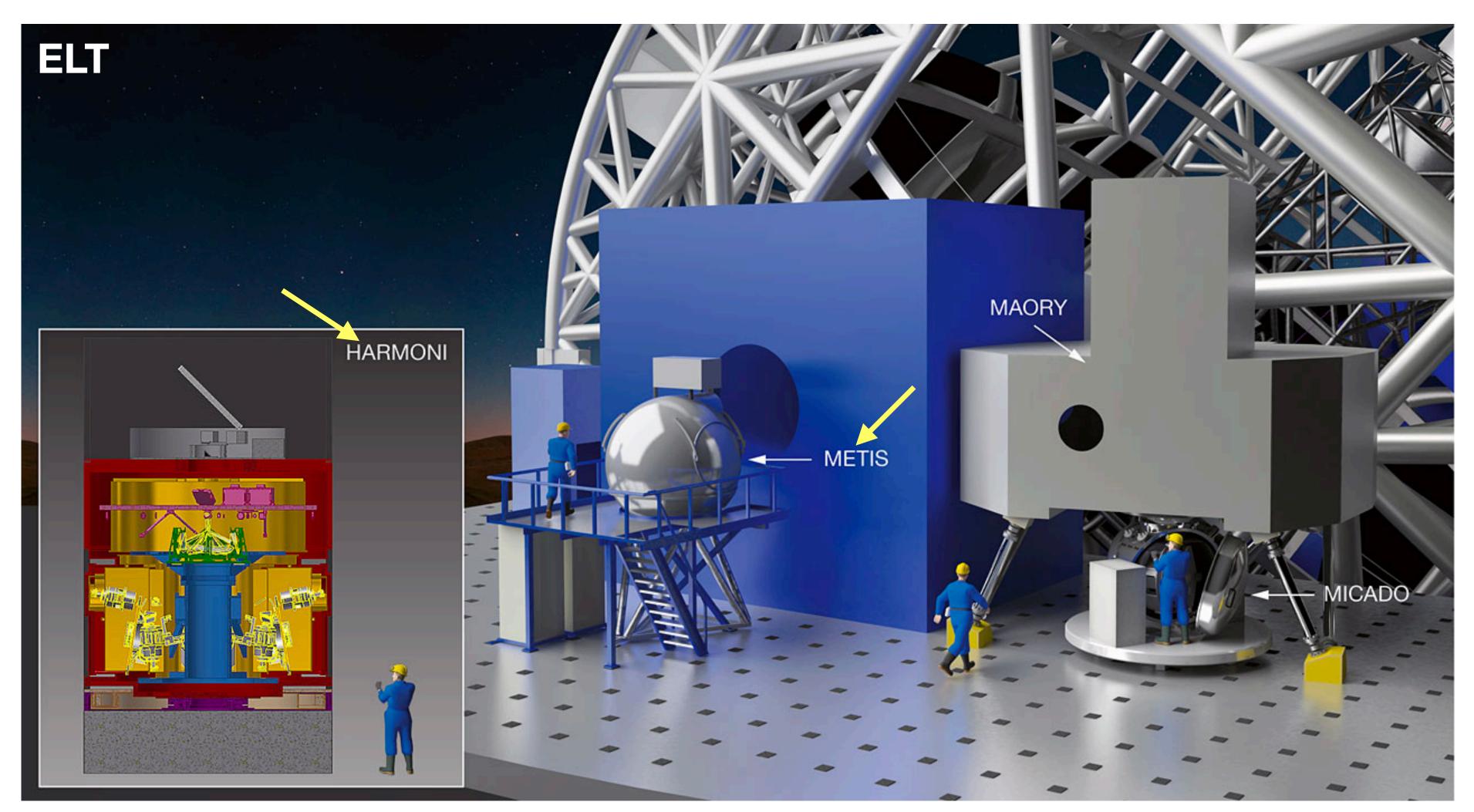
Integral Field Spectroscopy The importance of IFU spectroscopy, now and for the future



MUSE Data Reduction Works

Credit: ESO

Integral Field Spectroscopy The importance of IFU spectroscopy, now and for the future



Credit: NOVA/METIS/MAORY/MICADO/HARMONI

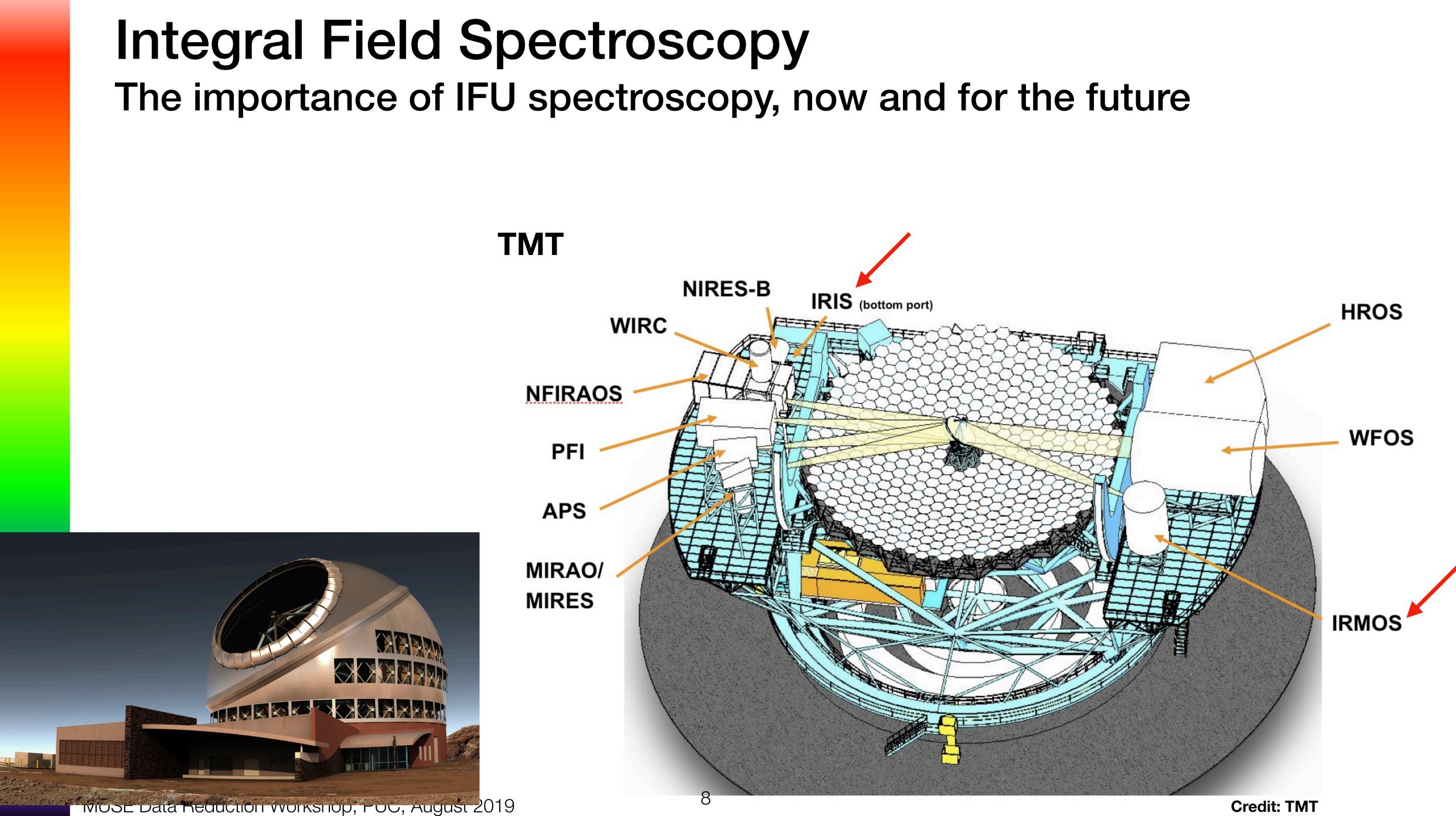
Integral Field Spectroscopy The importance of IFU spectroscopy, now and for the future



MUSE Data Reduction Workshop, PUC, August 2019

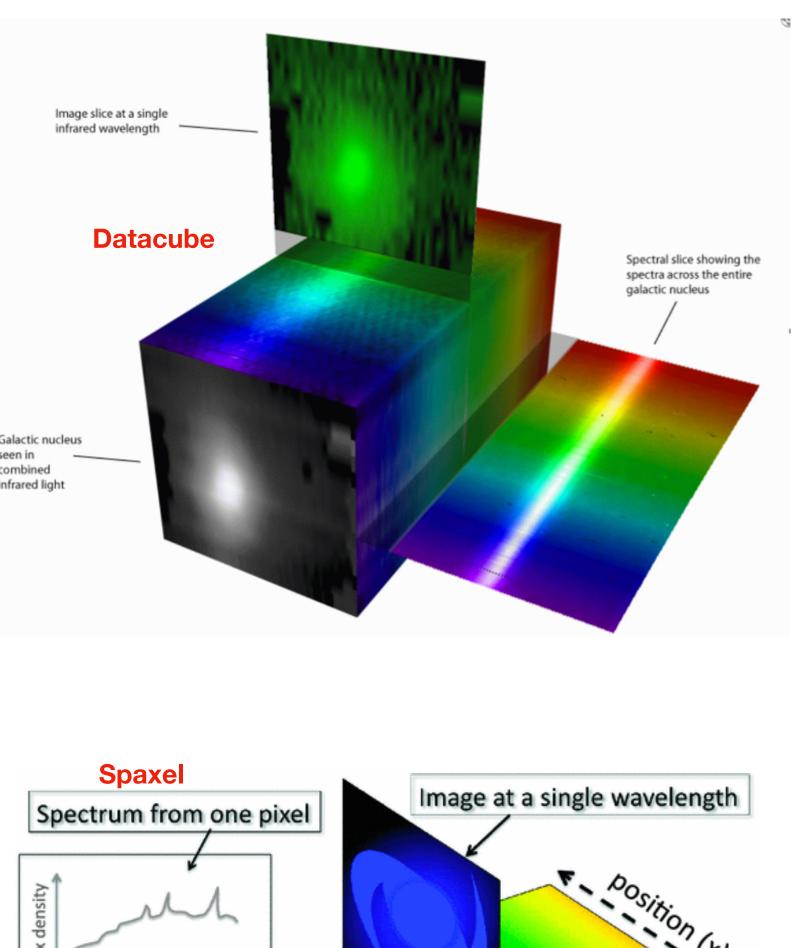
NEAR-IR IFU AND ADAPTIVE OPTICS IMAGER – GMTIFS

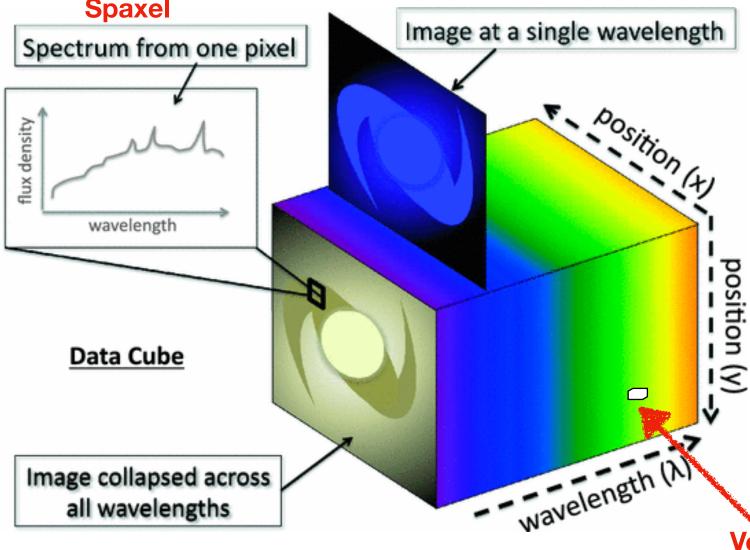




Integral Field Spectroscopy What is it?

- Sometimes referred to as 3D spectroscopy
- The final product is a **datacube**.
- A datacube is simply a series of narrow-band \bullet images
- The FOV is sampled as small aperture elements \bullet called **spaxels**, each of which has an associated spectrum (spaxel=spectral pixel)
- Each element in a datacube is called a **voxel**





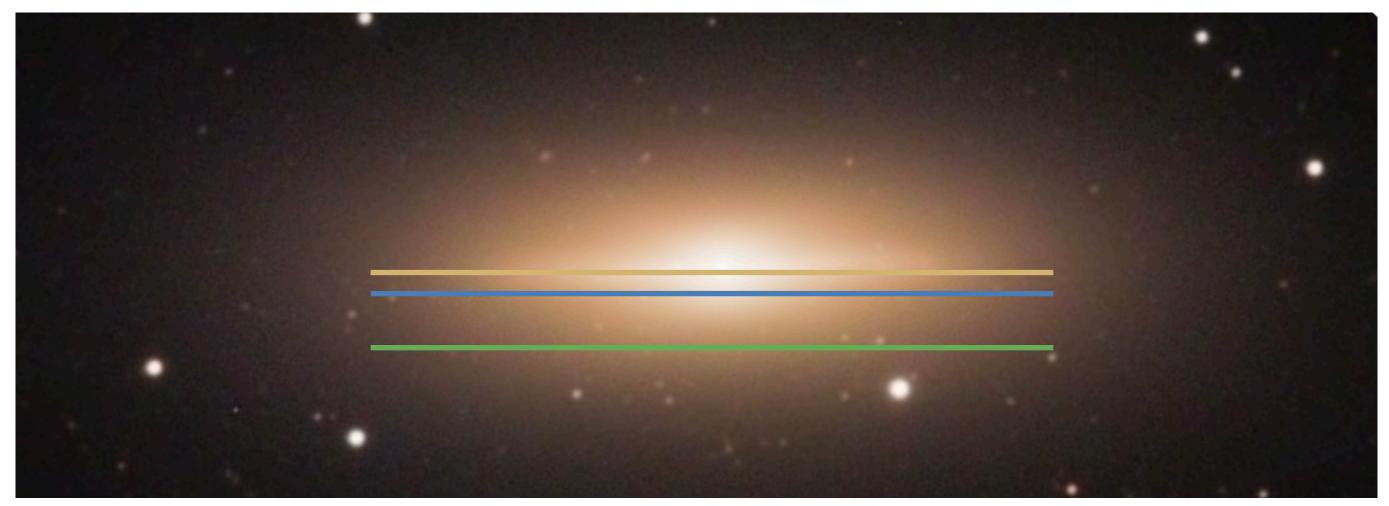


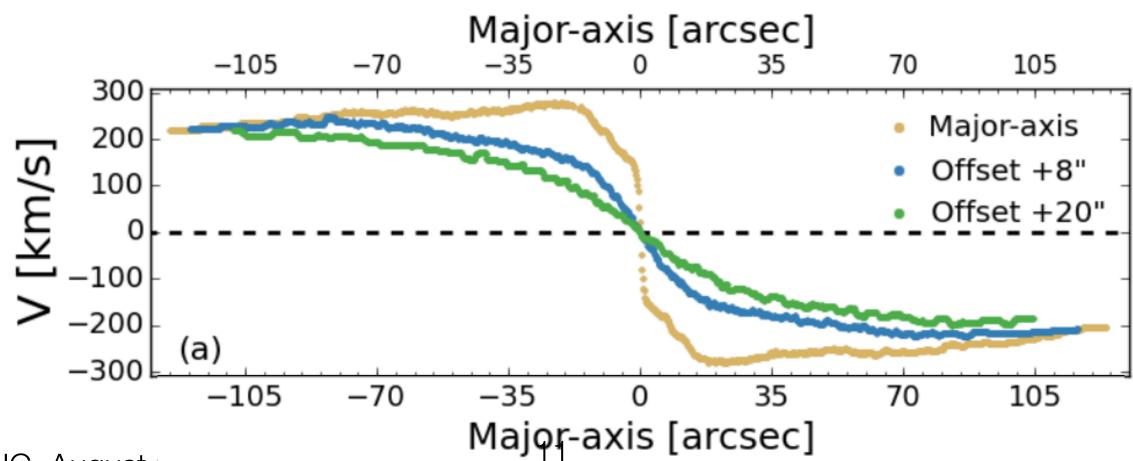




• Observe the whole object







MUSE Data Reduction Workshop, PUC, August 2013

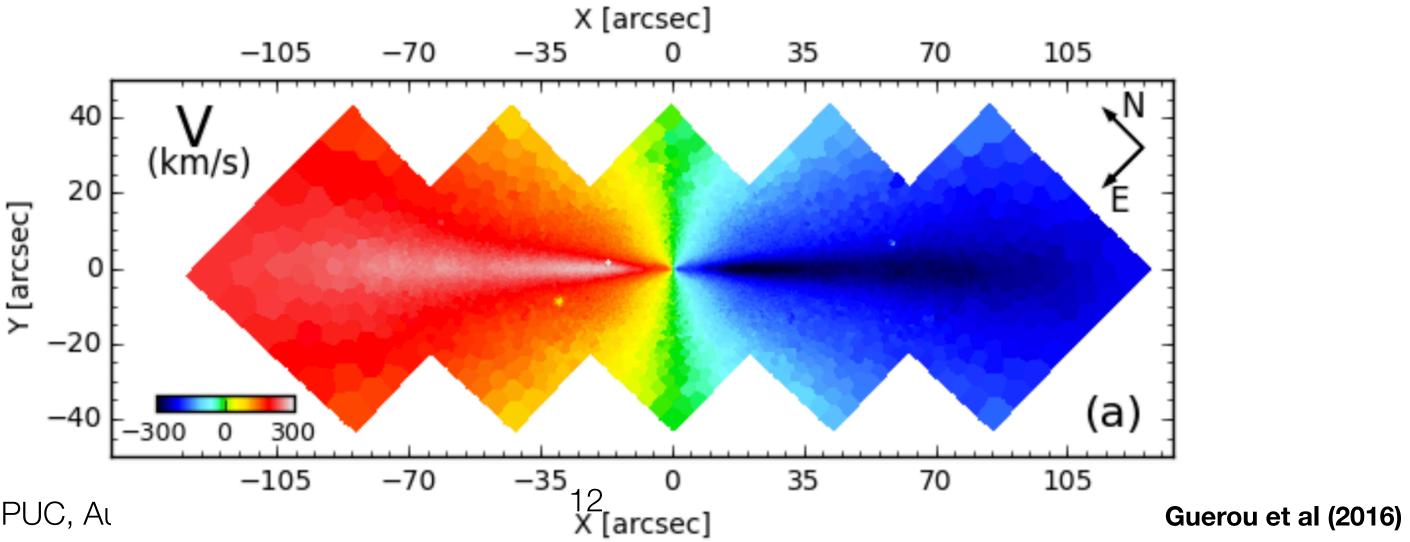
NGC 3115

Guerou et al (2016)

• Observe the whole object



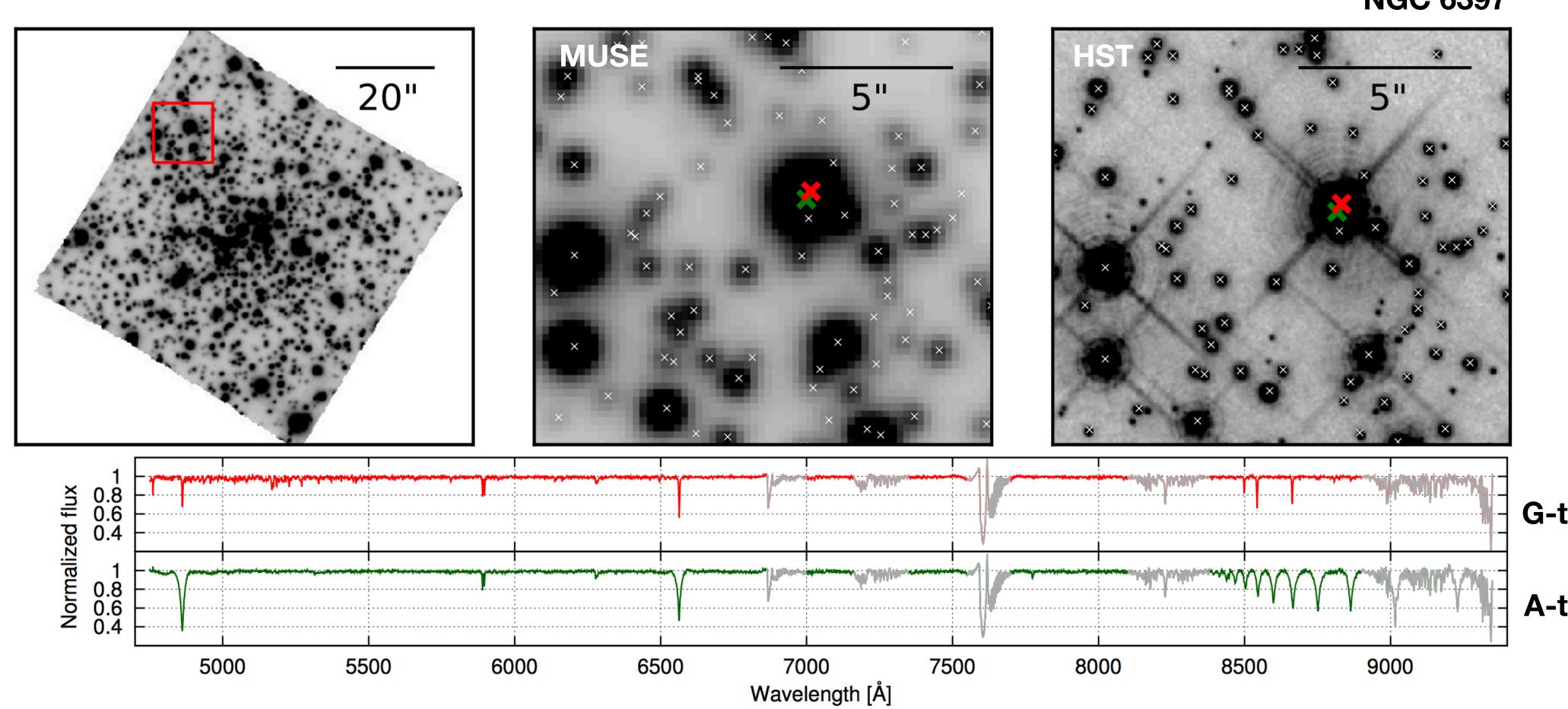




MUSE Data Reduction Workshop, PUC, Au

NGC 3115

• Deblend overlapping objects

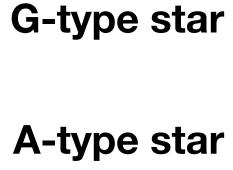


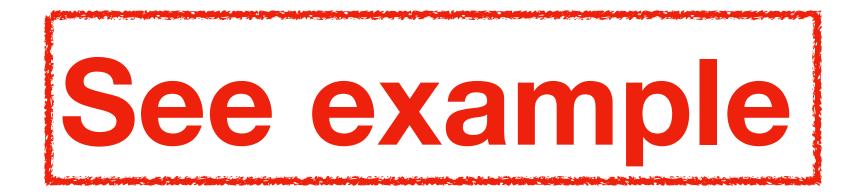
13

MUSE Data Reduction Workshop, PUC, August 2019

NGC 6397

Husser et al (2016)



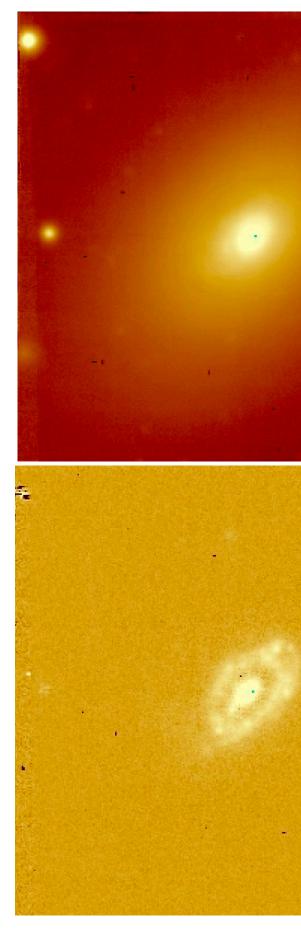


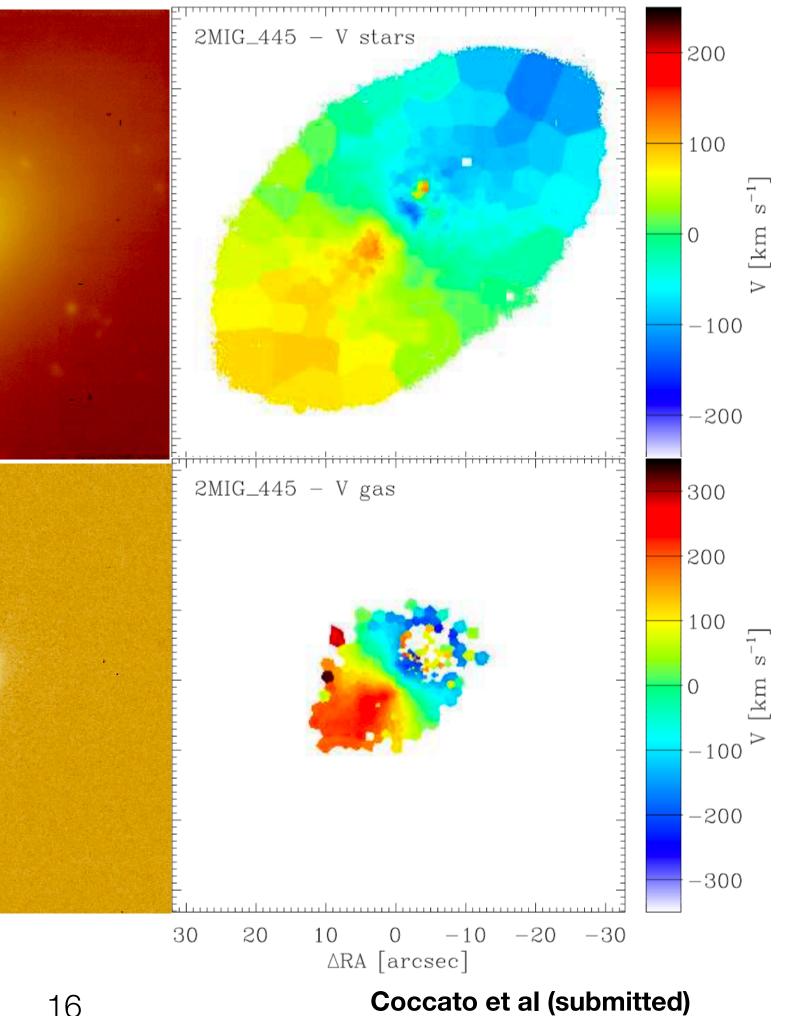
Integral F Advantages

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| ne documentation availabl functions registered. | e at: http://www.mpe.mpg.de/~ott/dpus | er Forkshop/datacubes/DATACUBE_FINAL.fits", 1) | | |
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MUSE Data Reduction Workshop

Stellar and Gas Kinematics





Gas Stripping

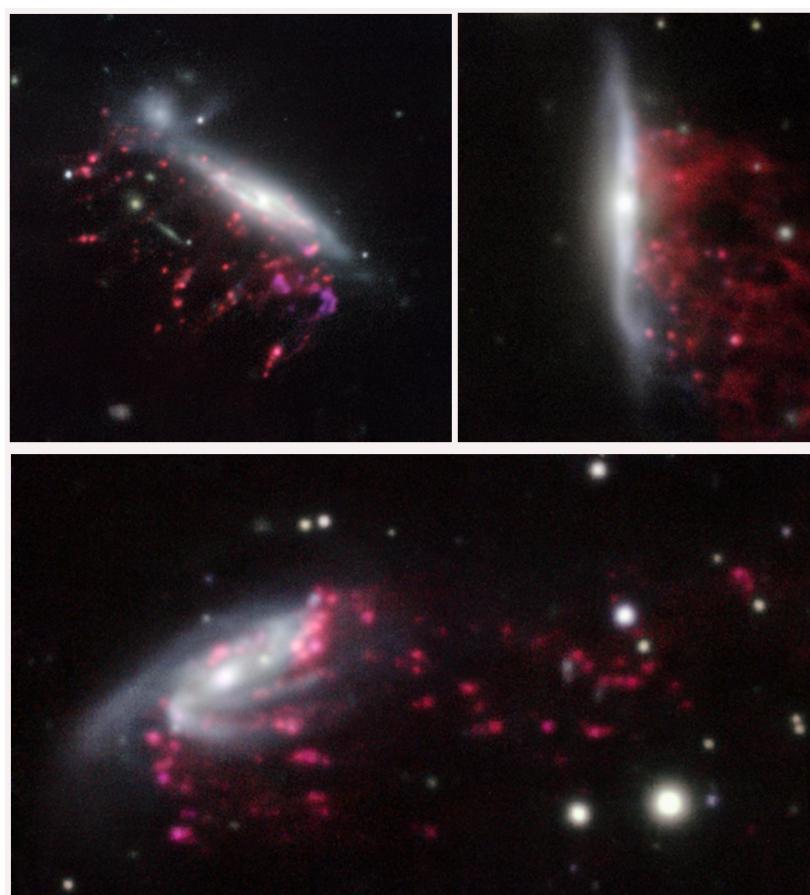
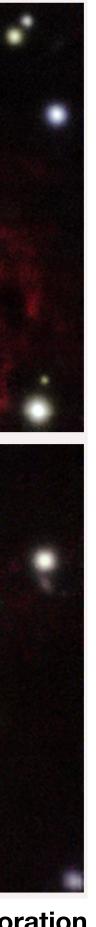
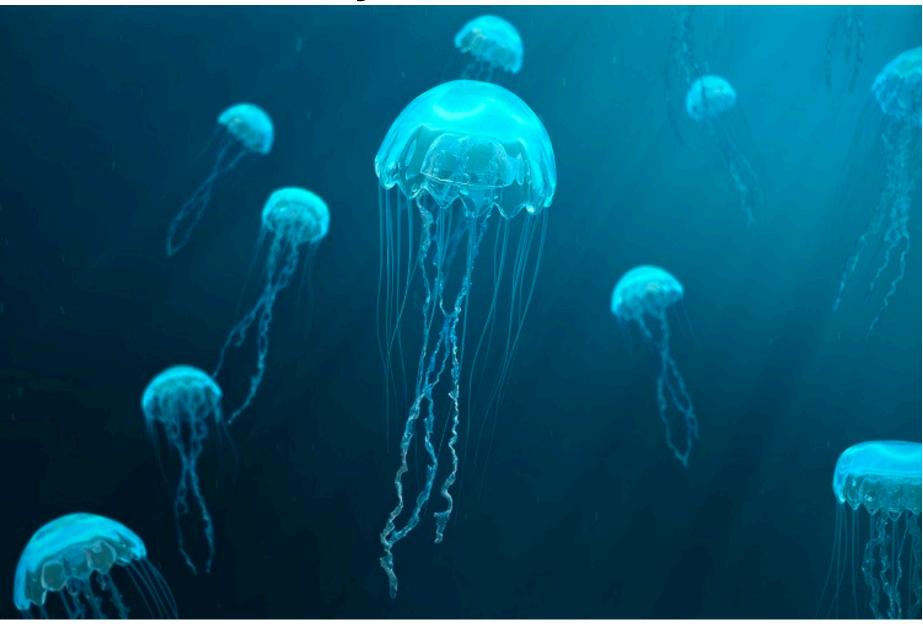


Image credit: ESO/GASP collaboration MUSE Data Reduction Workshop, PUC, August 2019

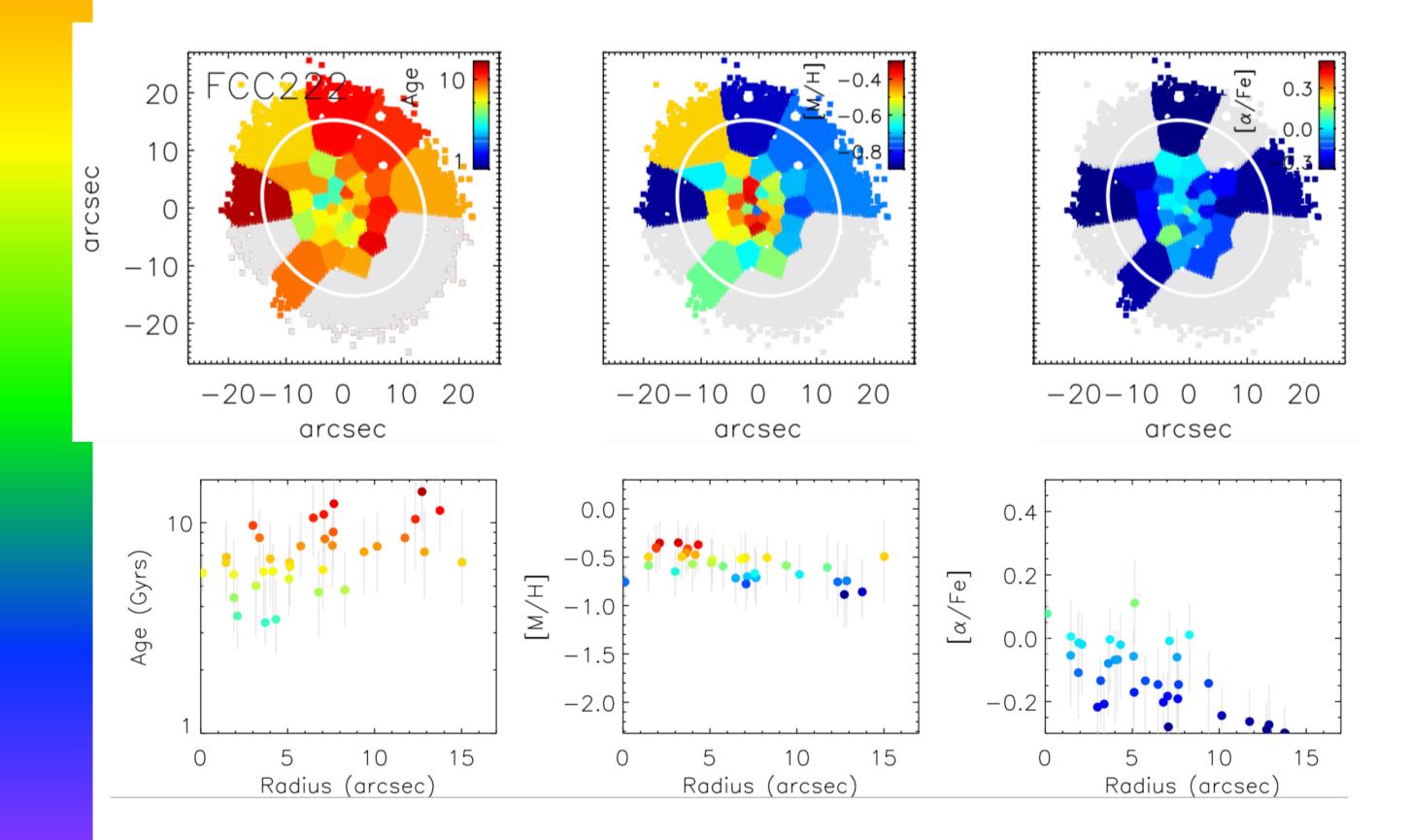


17

Also known as Jellyfish Galaxies

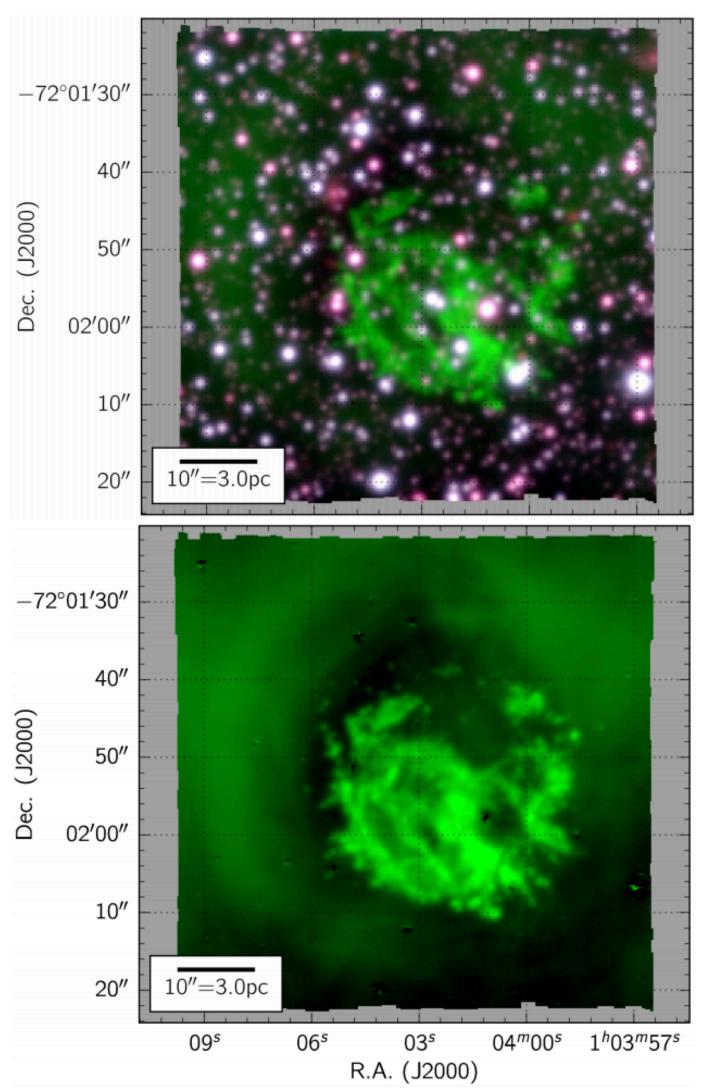


Stellar Populations



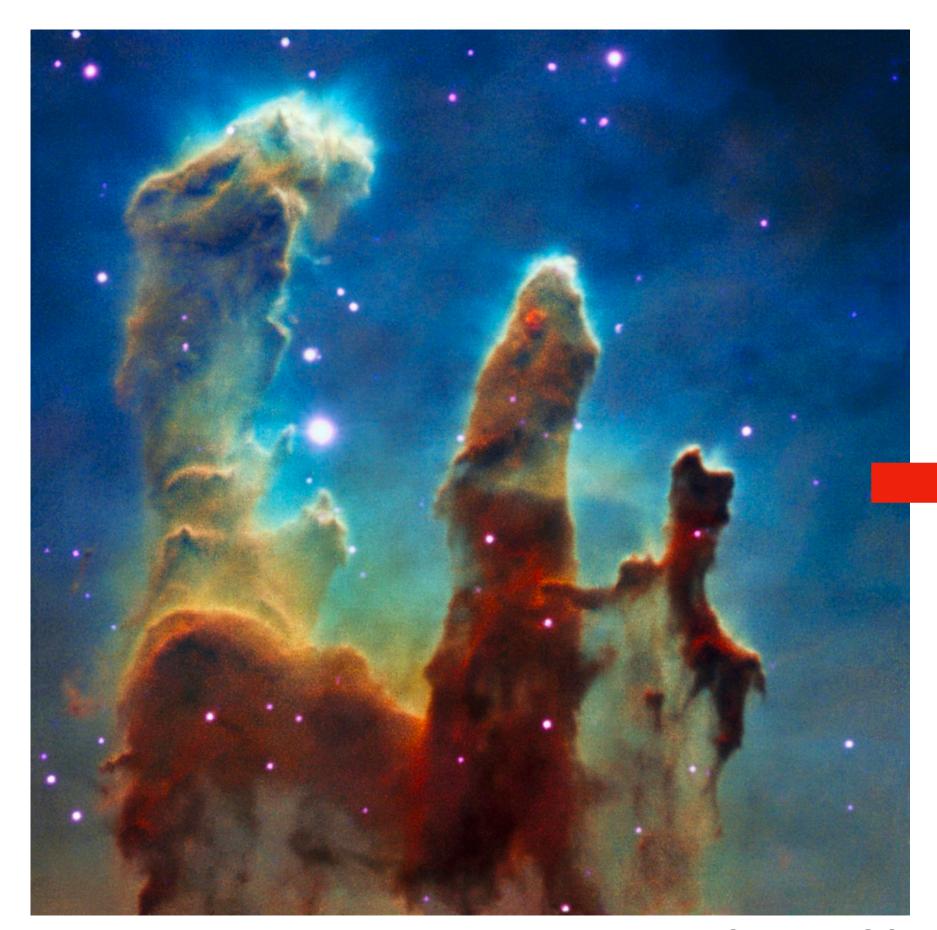
MUSE Data Reduction Workshop, PUC, August 2019

Mapping SNe Remnants

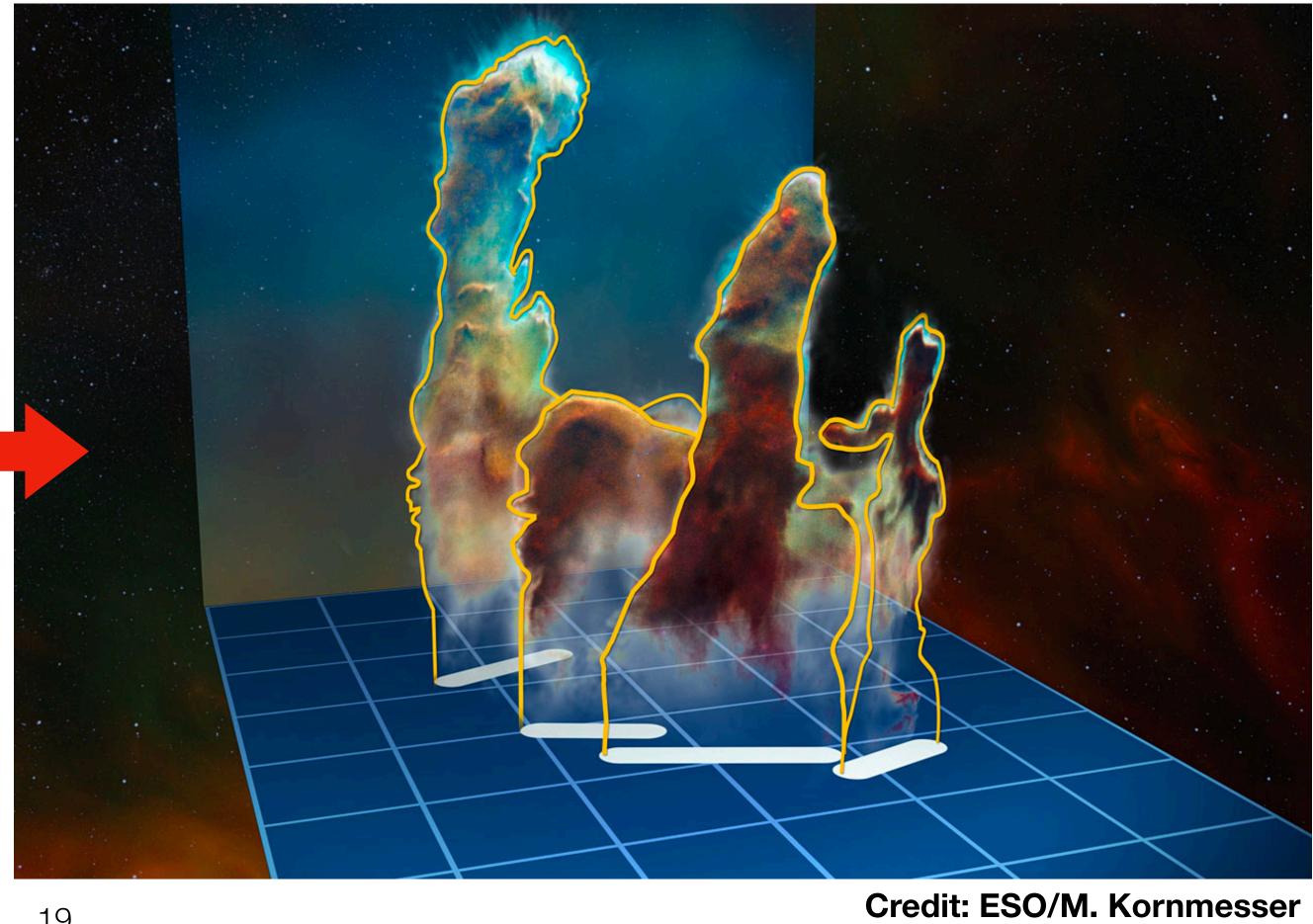


Vogt et al (2017)

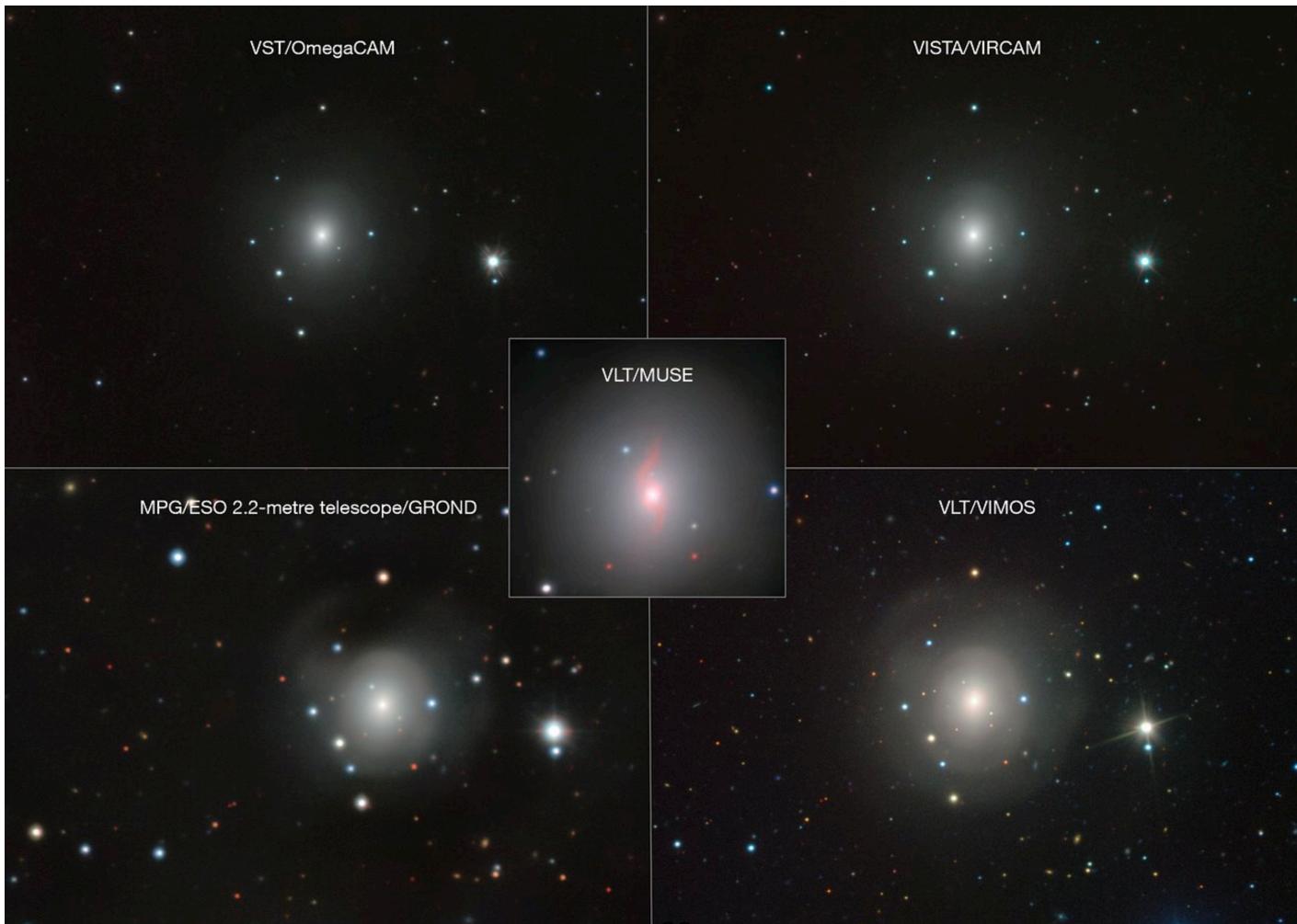
Determine 3D positions of targets in the FOV



Credit: ESO MUSE Data Reduction Workshop, PUC, August 2019



3 colour images



MUSE Data Reduction Workshop, PUC, August ²⁽Credit: VLT/VIMOS. VLT/MUSE, MPG/ESO 2.2-metre telescope/GROND, VISTA/VIRCAM, VST/OmegaCAM



3 colour images (and videos!)

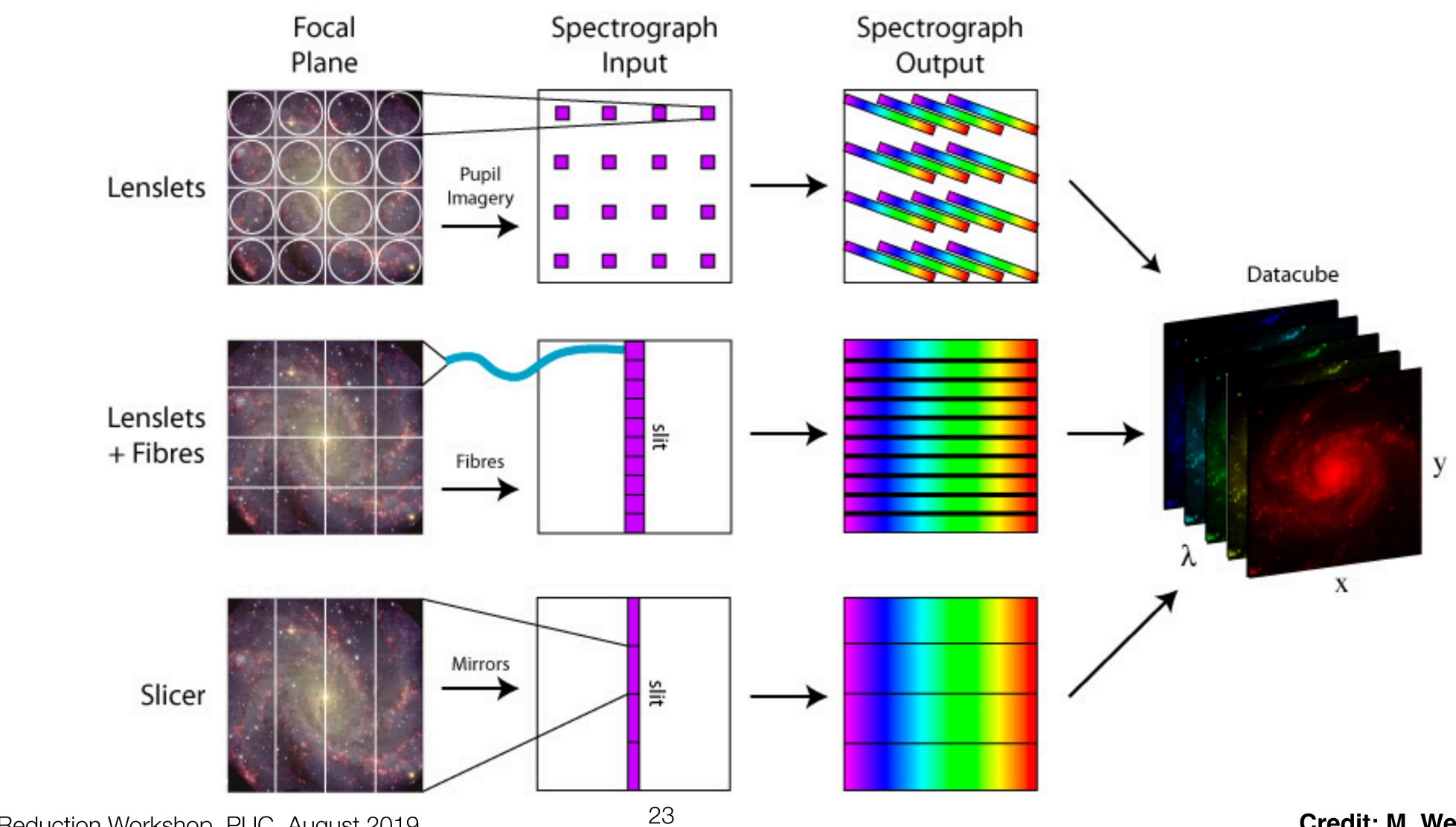




Credit: ESO/MUSE consortium/R. Bacon

MUSE The Multi-Unit Spectroscopic Explorer

Integral Field Spectroscopy IFS techniques



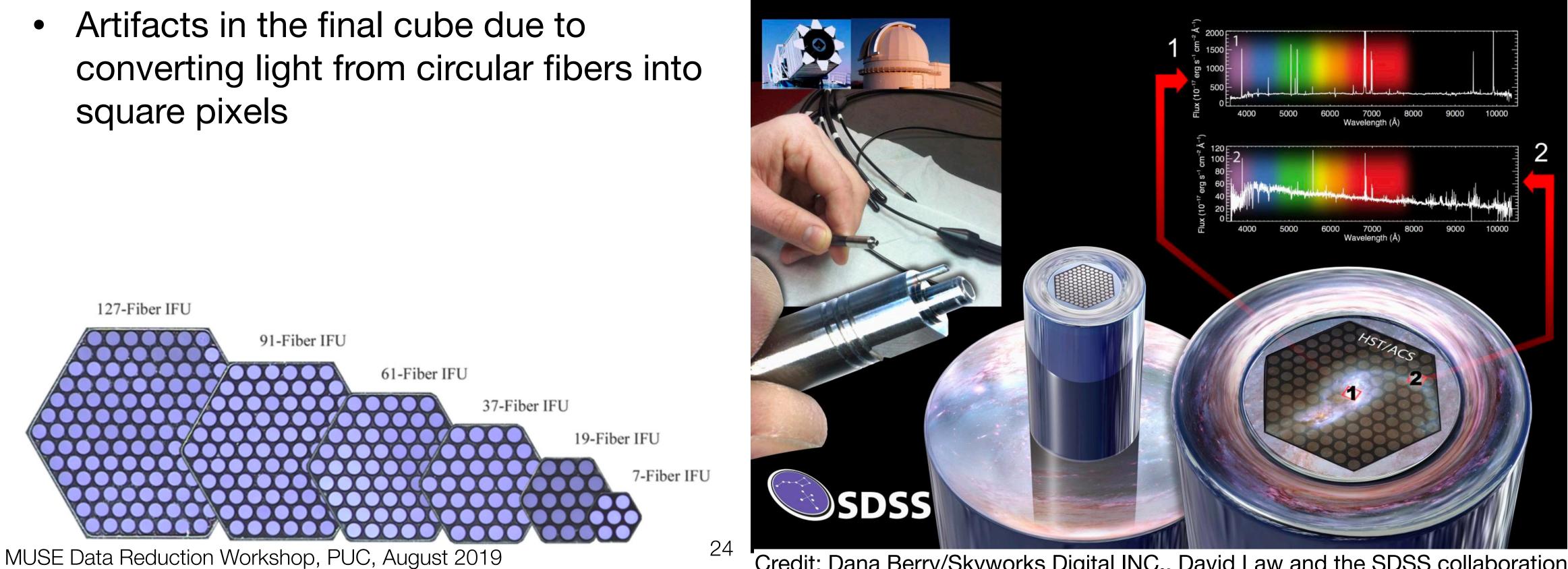
MUSE Data Reduction Workshop, PUC, August 2019

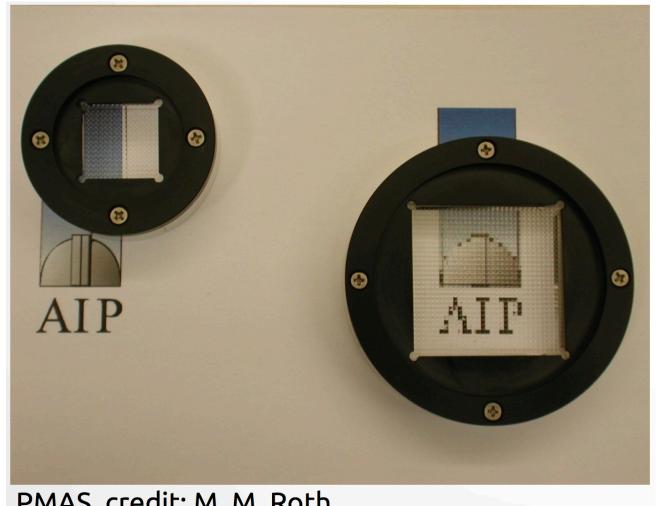
Credit: M. Westmoquette



Integral Field Spectroscopy **IFS** using fibers

- e.g. MaNGA
- Fiber-bundles of different sizes
- Dither pattern requires to fill in the gaps \bullet between fibers
- Artifacts in the final cube due to square pixels



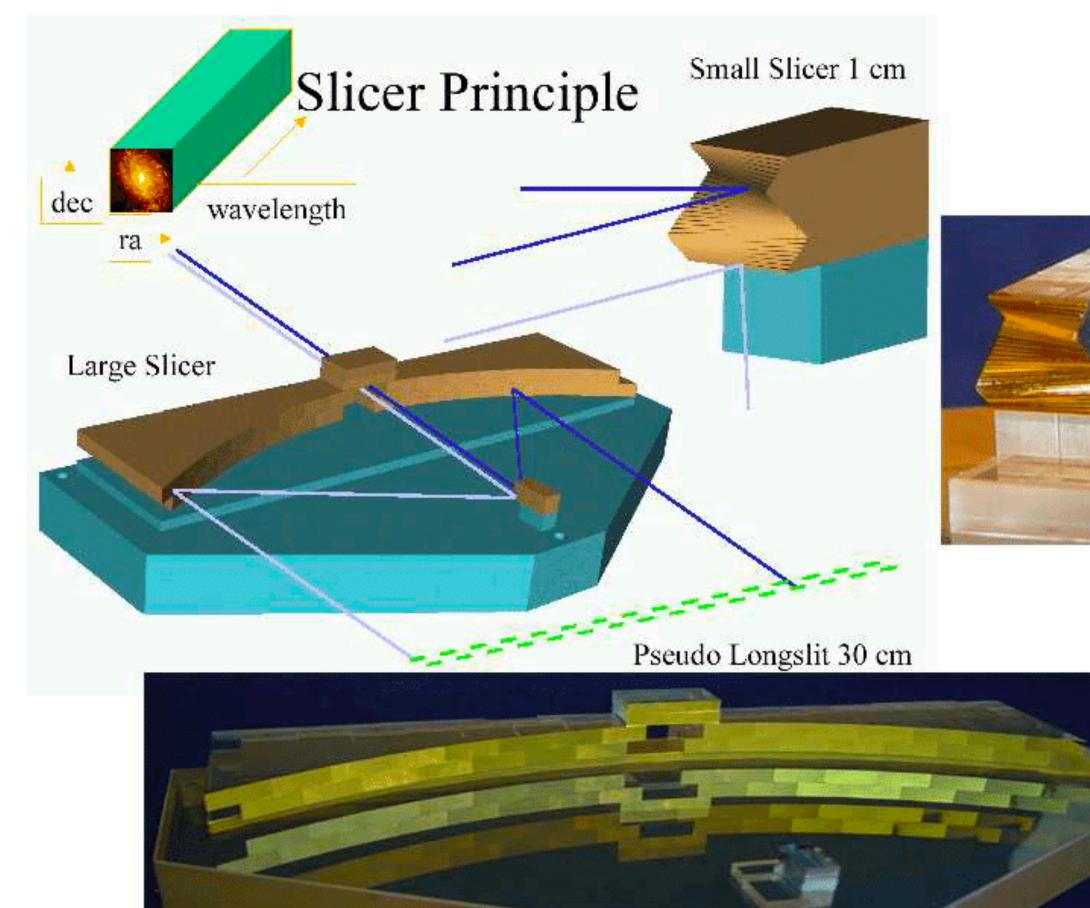


PMAS, credit: M. M. Roth

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

Integral Field Spectroscopy **IFS using slicers**

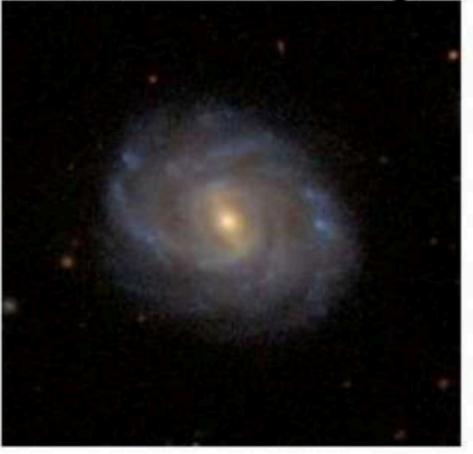
- e.g. SINFONI \bullet
- Input image is split up into slit lets using \bullet an image slicer
- Oldest technique for IFU \bullet
- Most efficient use of CCD in terms of percentage coverage of FOV
- BUT, optics are challenging to \bullet manufacture.







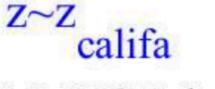
Surveys Unless you're a member of the team, you have no say in the targets SDSS 90"x90" image Atlas3D

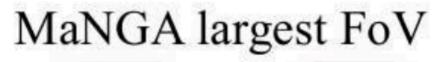


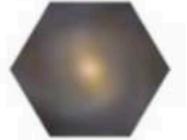
CALIFA (V500/V1200)

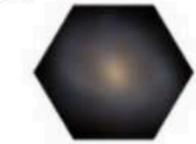












FoV~1.5Re

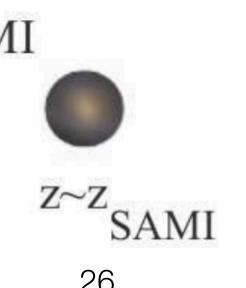


Z~Z califa



z~z Atlas3D

~2.5Re



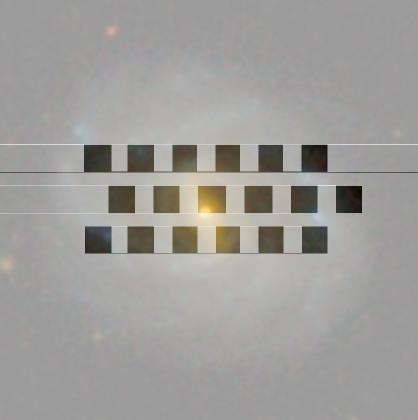
Instrument You can submit proposals to observe the target you are interested in

KCWI (Keck II)

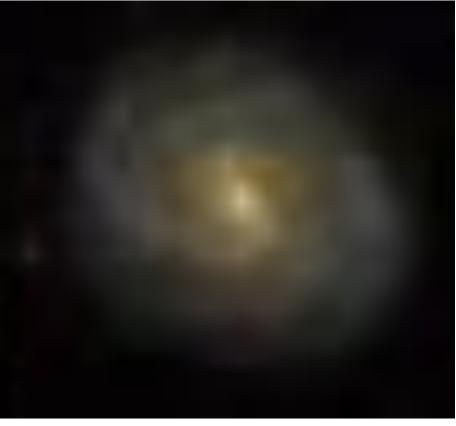




KMOS (ESO)

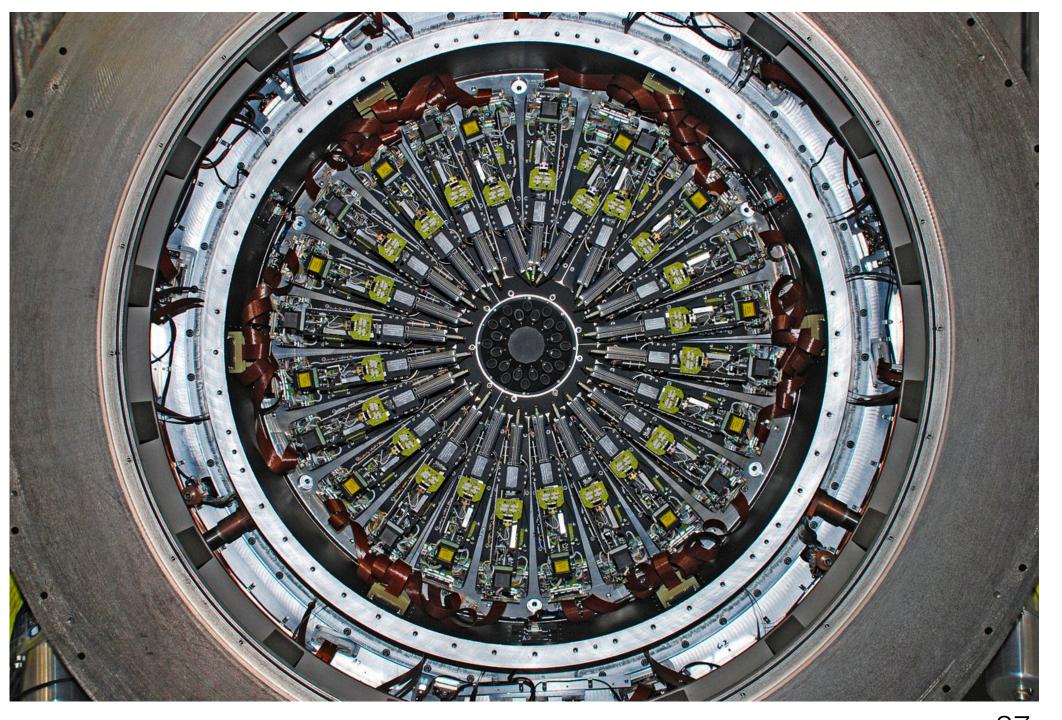


WEAVE (WHT)



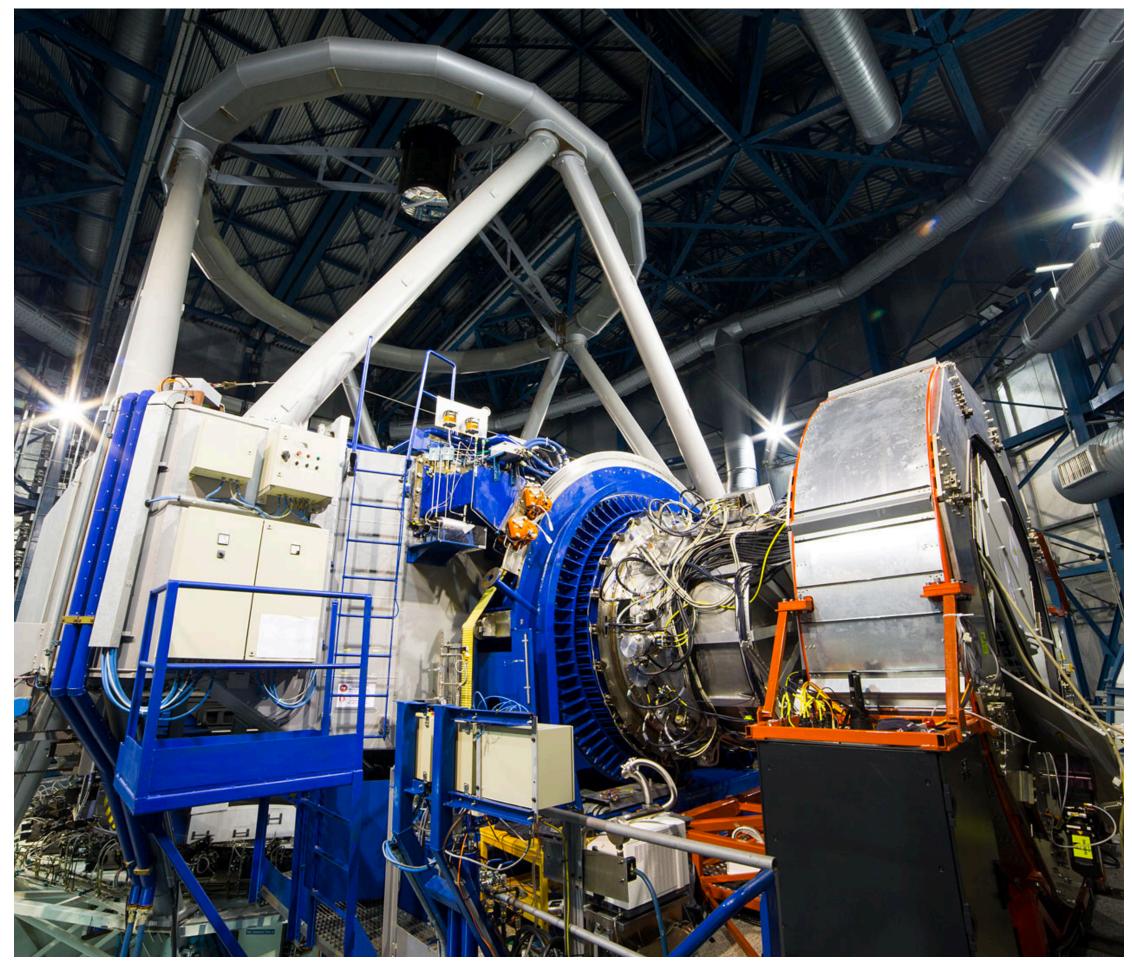


- <u>KMOS</u>
- 24 deployable IFUs, each with a FOV \bullet 2.8"x2.8" and spatial resolution 0.2"/pixel
- Infrared lacksquare



MUSE Data Reduction Workshop, PUC, August 26redit: STFC/UKATC/ESO

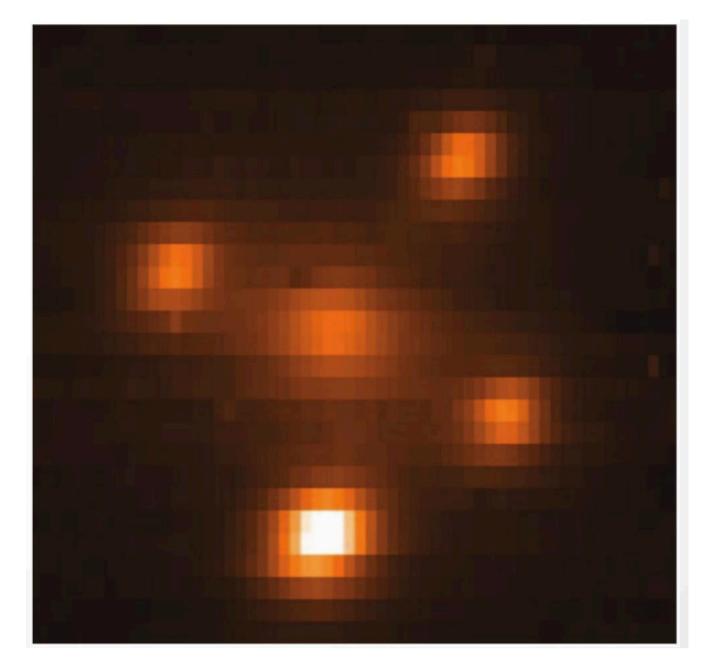




Credit: ESO/G. Lombardi

• <u>SINFONI</u>

- AO assisted IR IFS
- FOV from 0.8"x0.8" to 8"x8"
- One of the most successful IFS
- Recently decommissioned :-(



MUSE Data Reductionstein Gross, Bon Aet estal (2004)

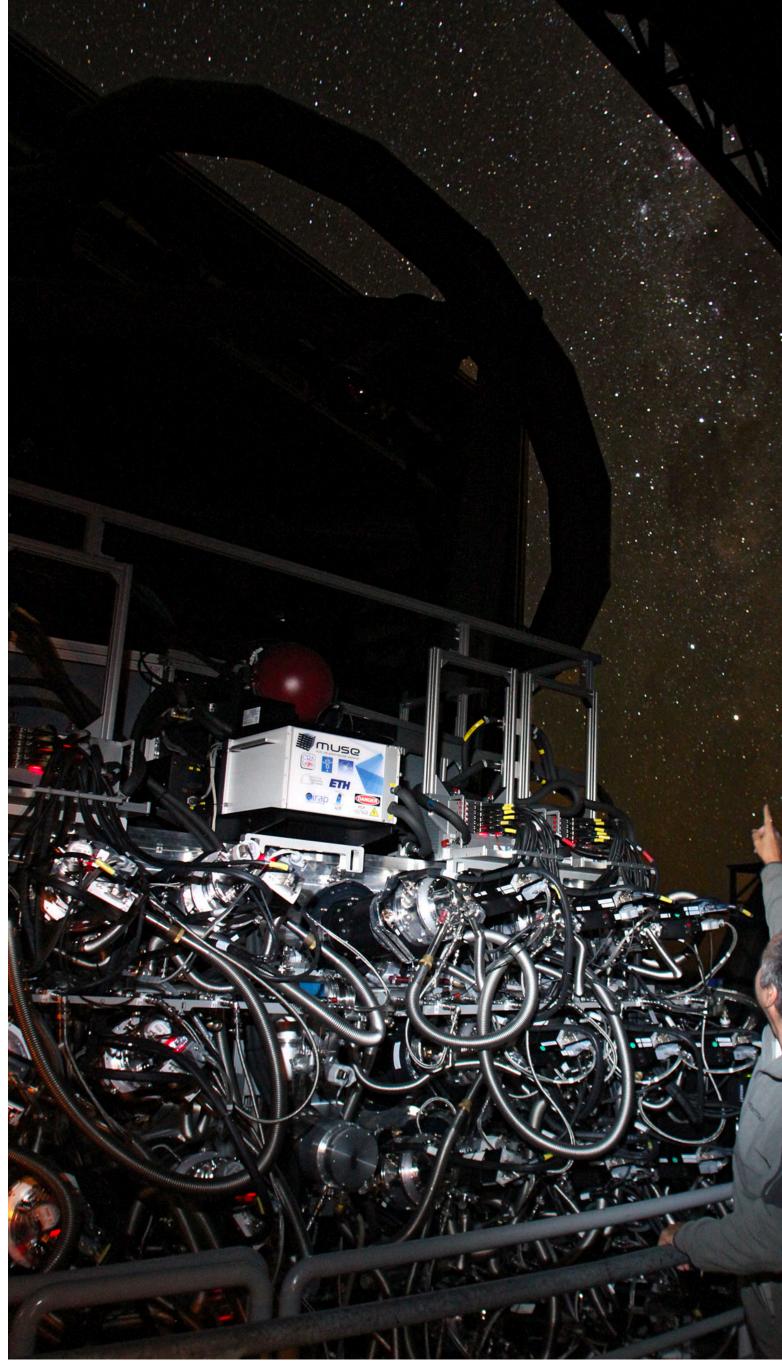




- <u>ERIS</u>
- IR IFU and imager
- Will recycle the SINFONI detector :-)
- First light 2020



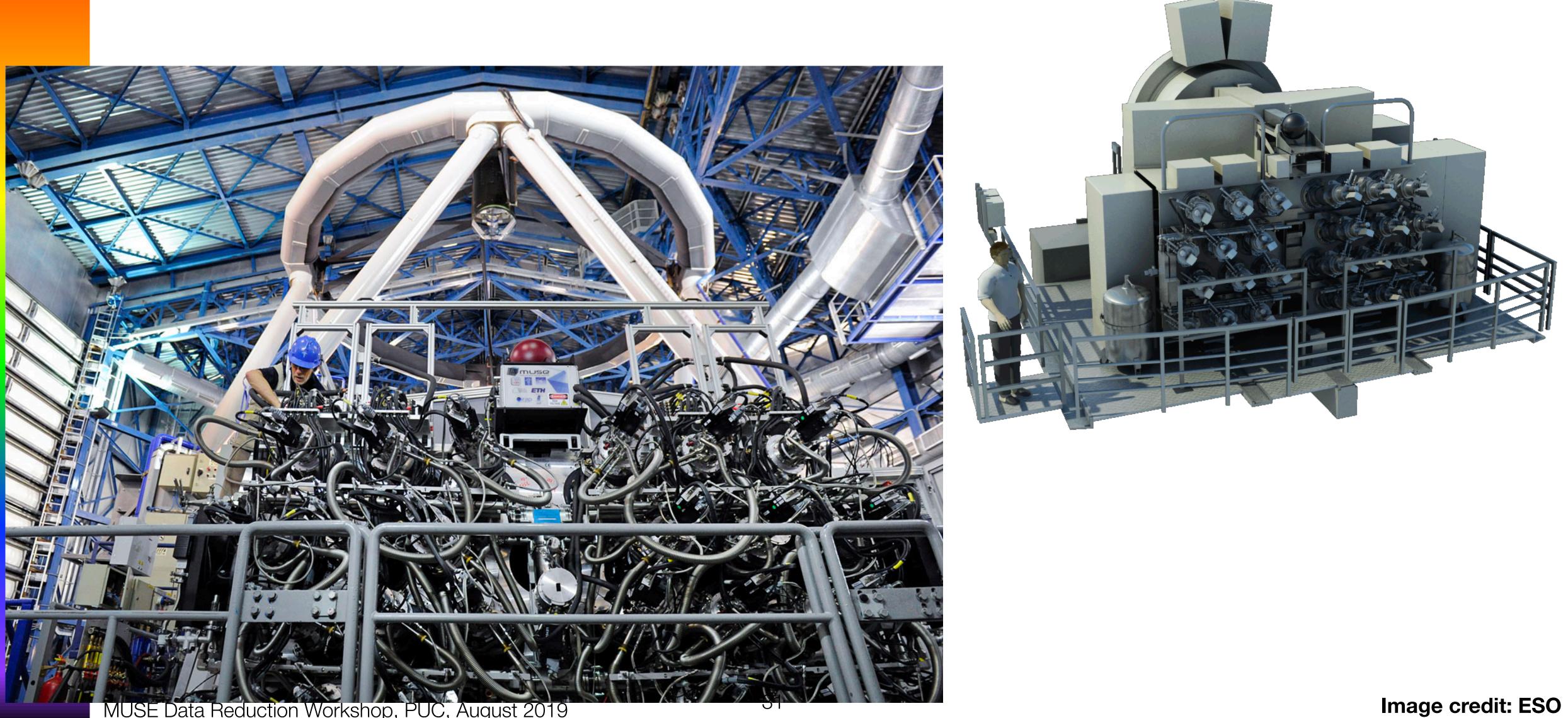
- **MUSE**
- Optical IFU with widest FOV currently in operation
- FOV 1'x1' (WFM) lacksquare
- Spaxel size 0.2"/pixel (WFM)
- Spectral resolution 2000-4000
- In operation since 2014



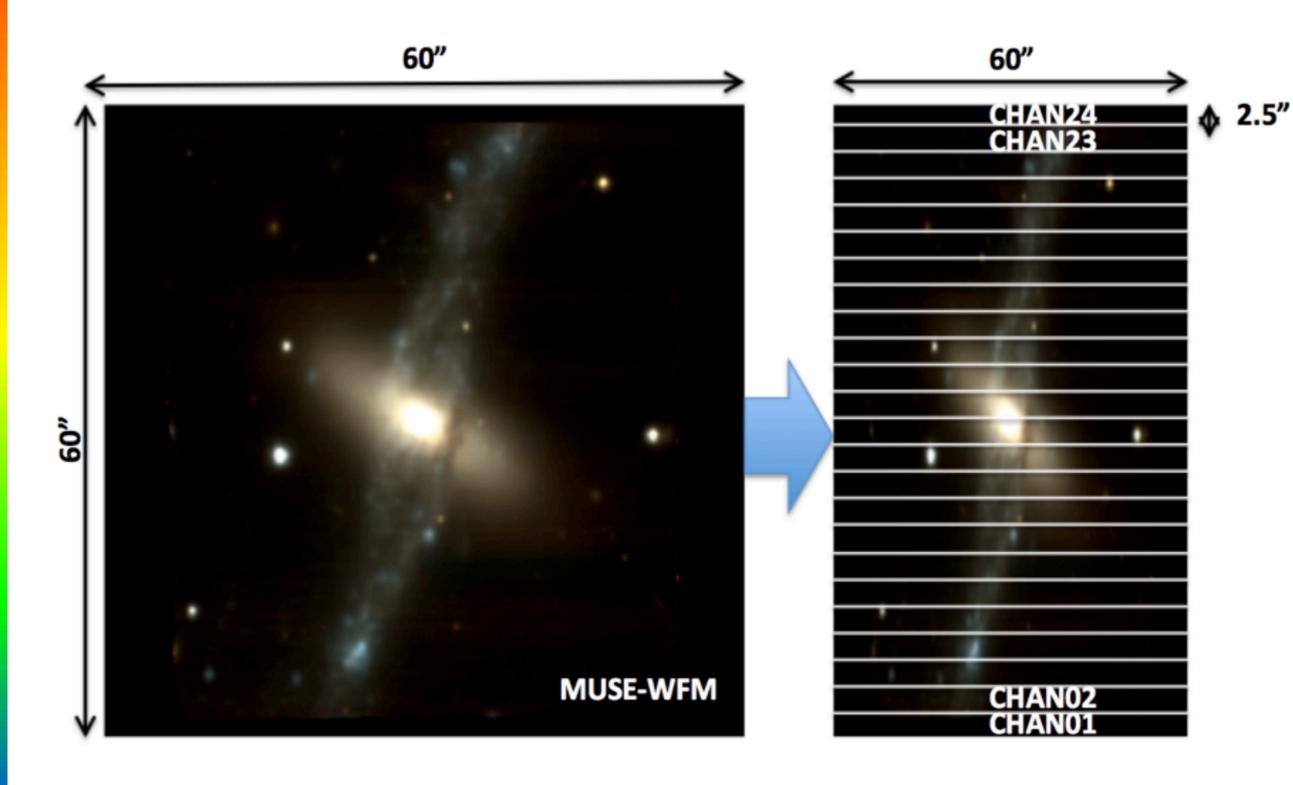
Credit: ESO/Ghaouti Hansali/Fernando Selman



MUSE: Multi-Unit Spectroscopic Explorer

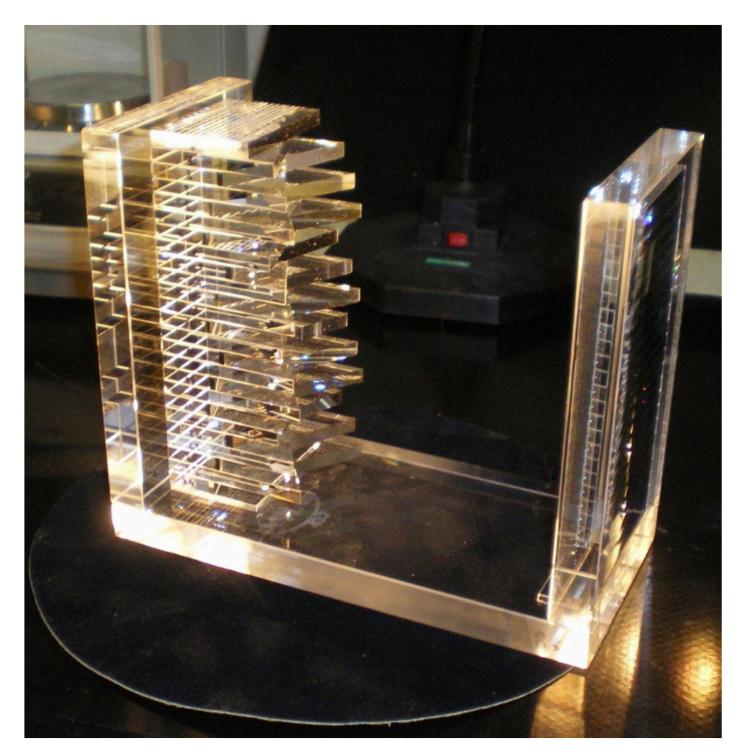


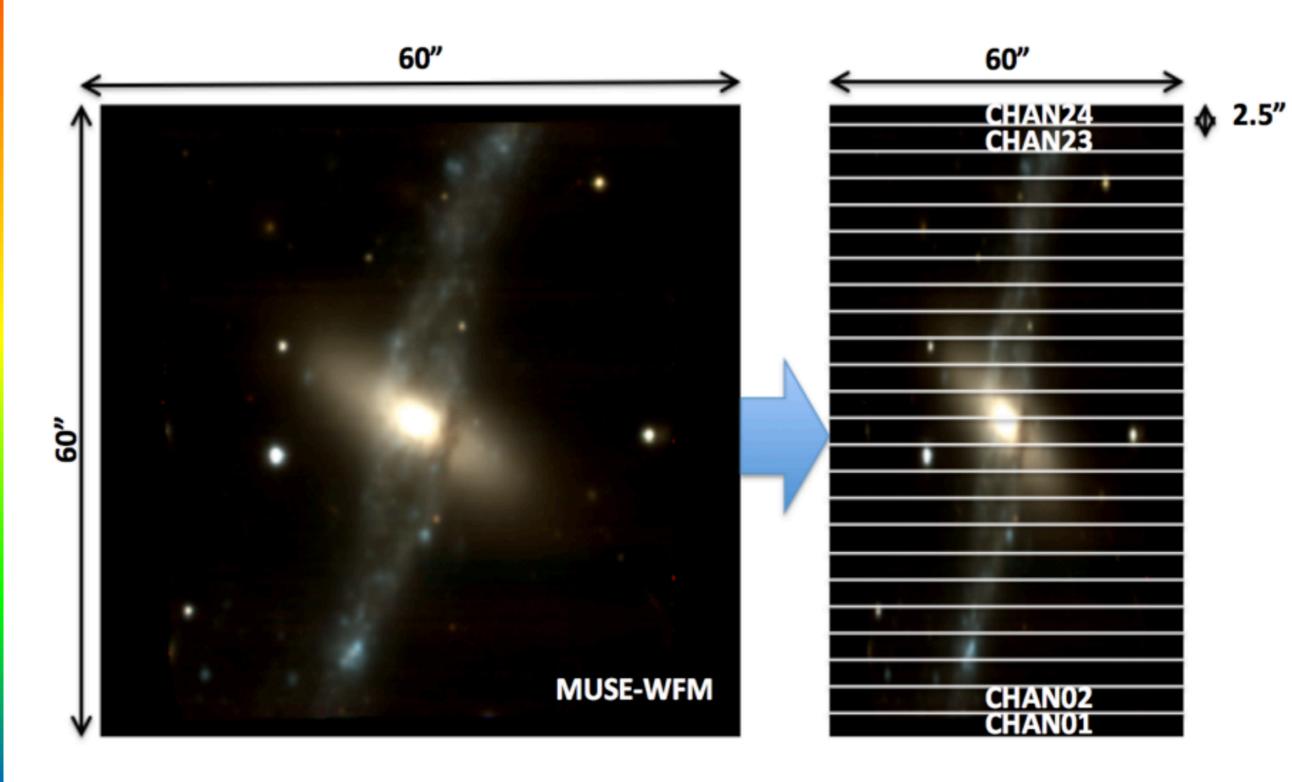




MUSE Data Reduction Workshop, PUC, August 2019

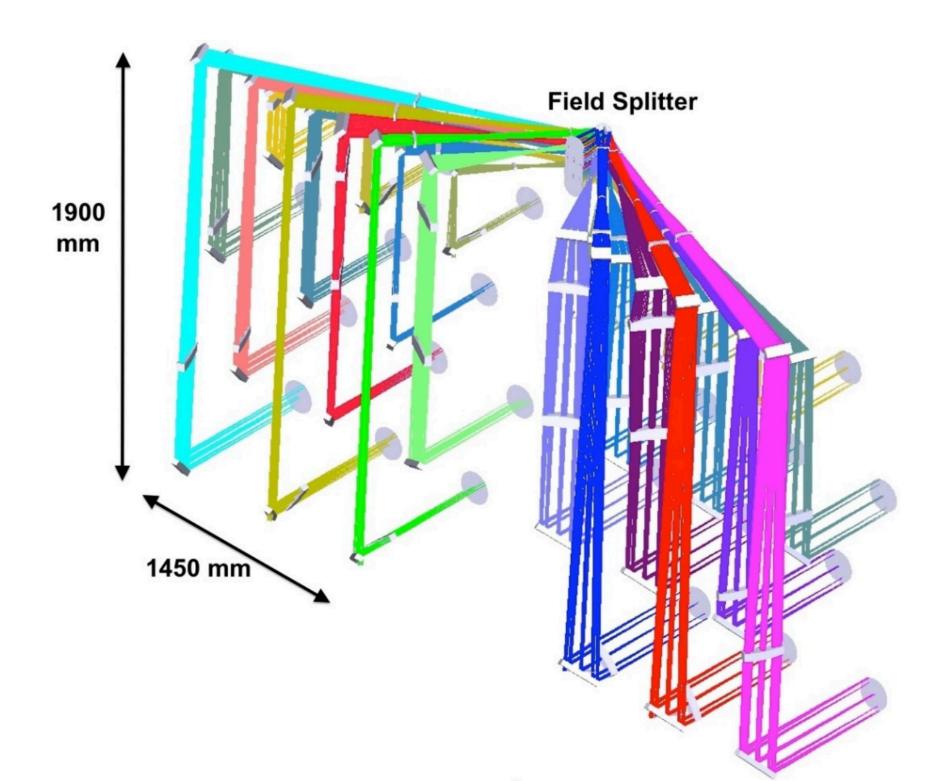
Beam Splitter Splits up the image into 24 segments



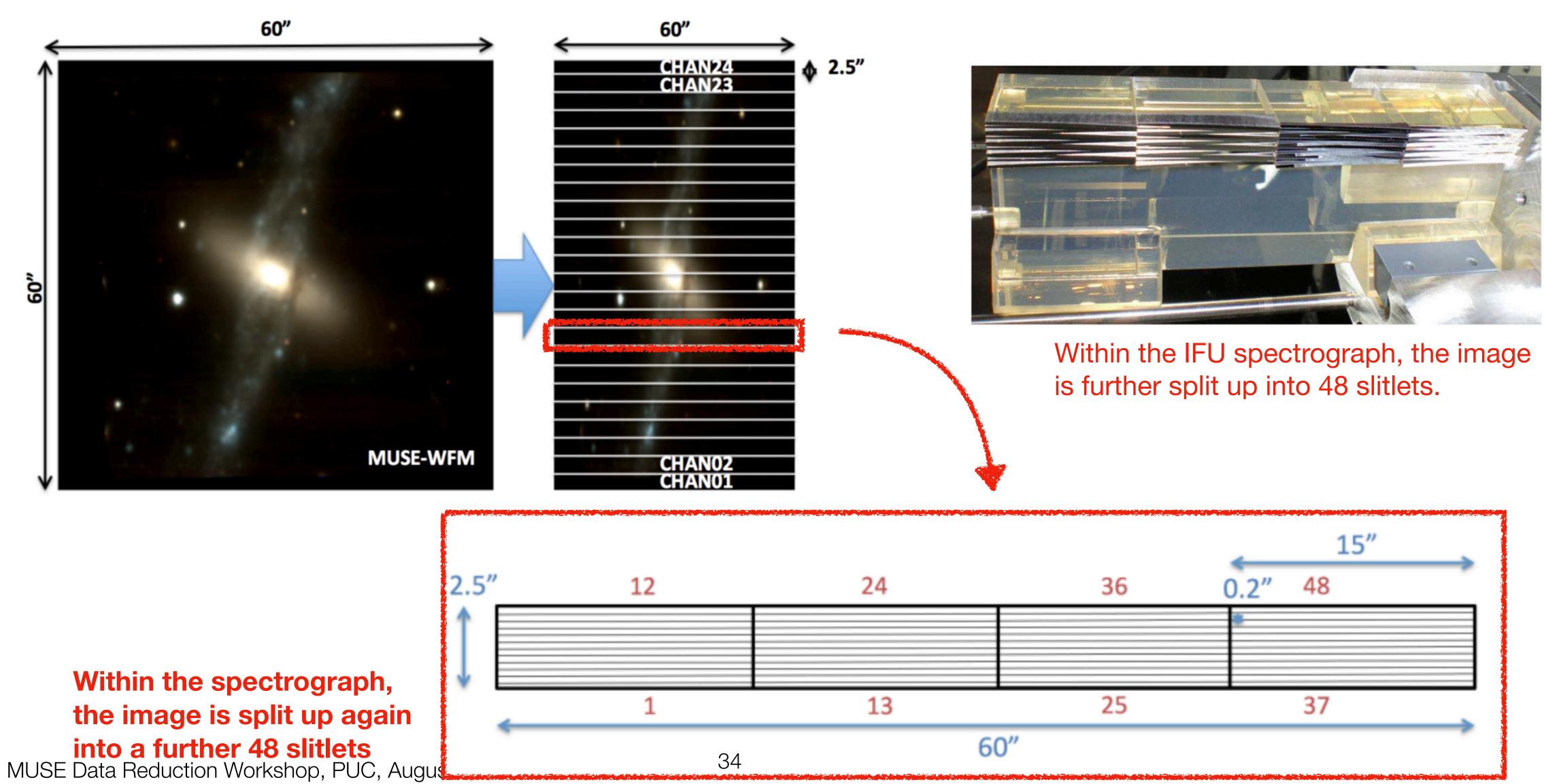


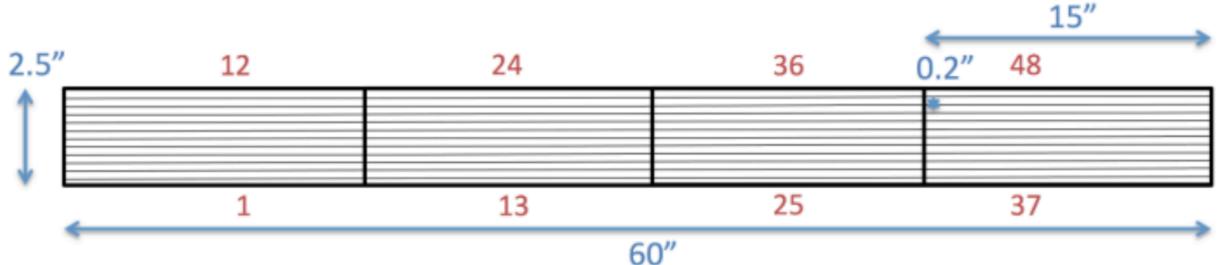
MUSE Data Reduction Workshop, PUC, August 2019

Each segmented image is directed to a separate IFU spectrograph

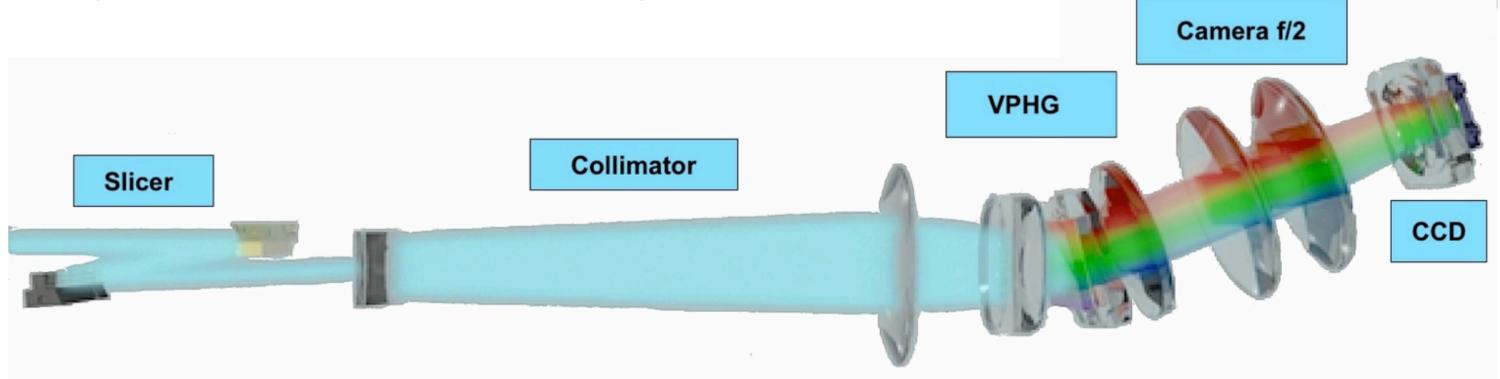






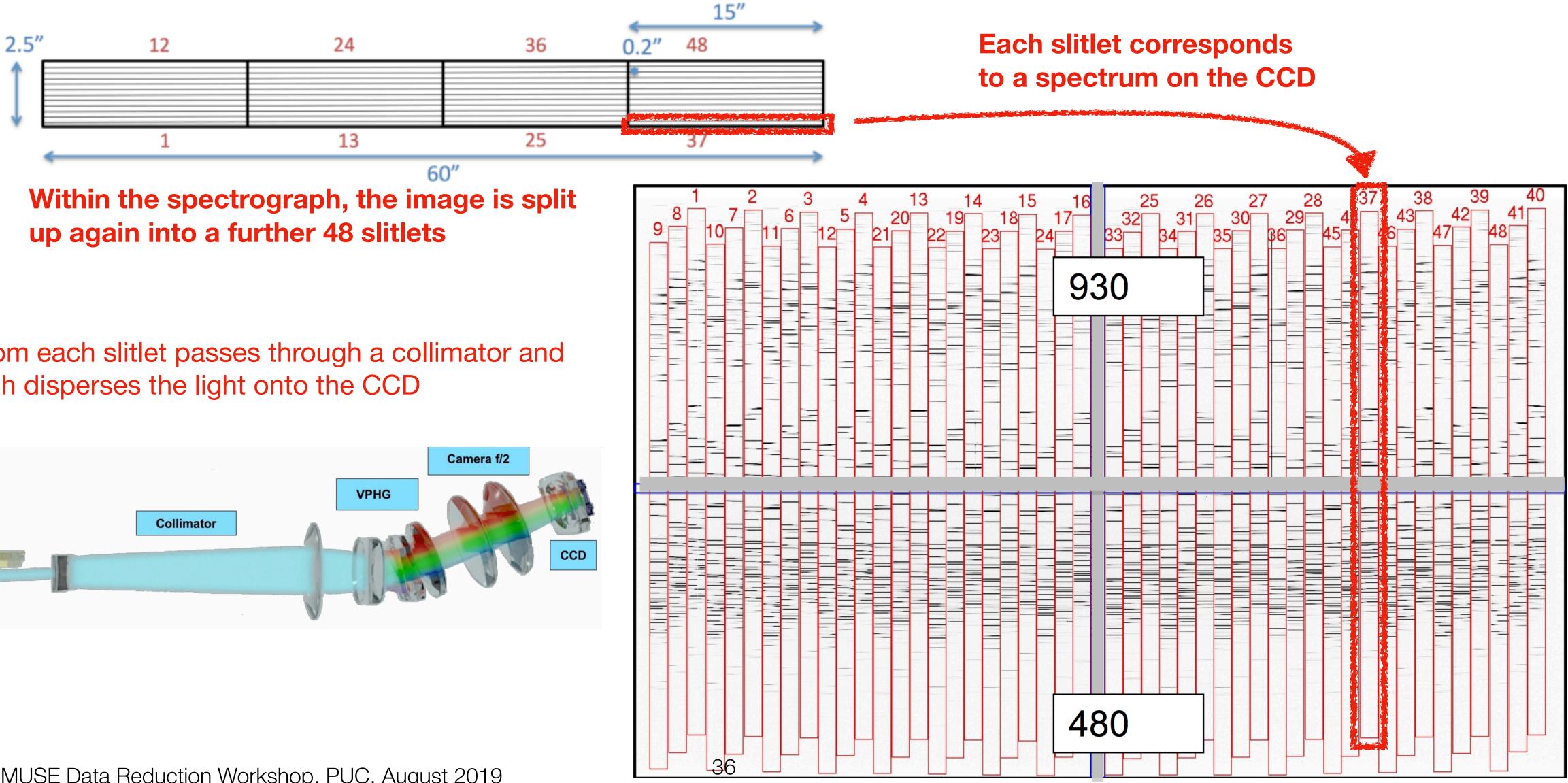


Within the spectrograph, the image is split up again into a further 48 slitlets

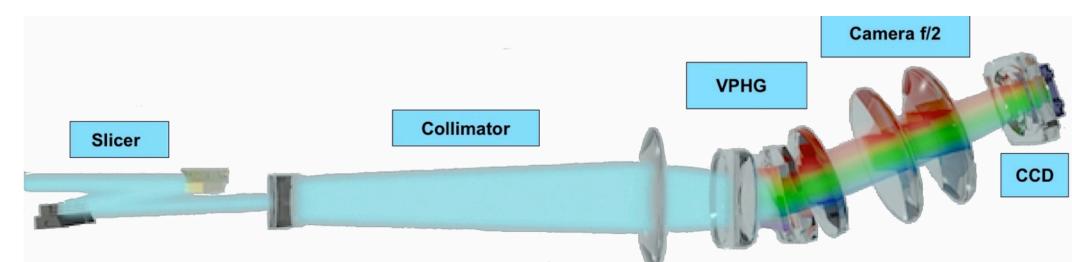


MUSE Data Reduction Workshop, PUC, August 2019

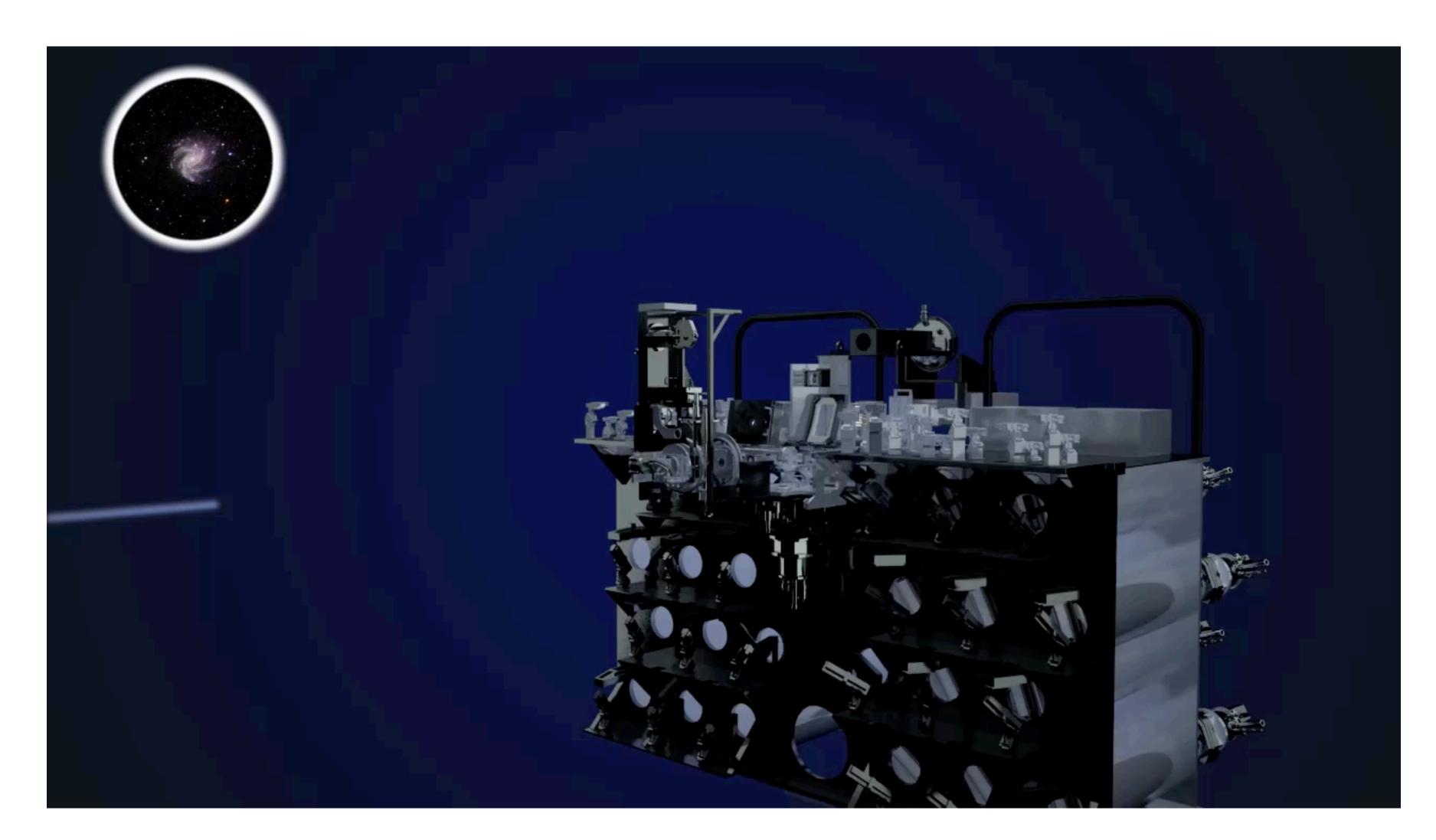
The light from each slitlet passes through a collimator and grism, which disperses the light onto the CCD



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



MUSE: Multi-Unit Spectroscopic Explorer A Journey Through MUSE



MUSE Data Reduction Workshop, PUC, August 2019

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 2 nd 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 |

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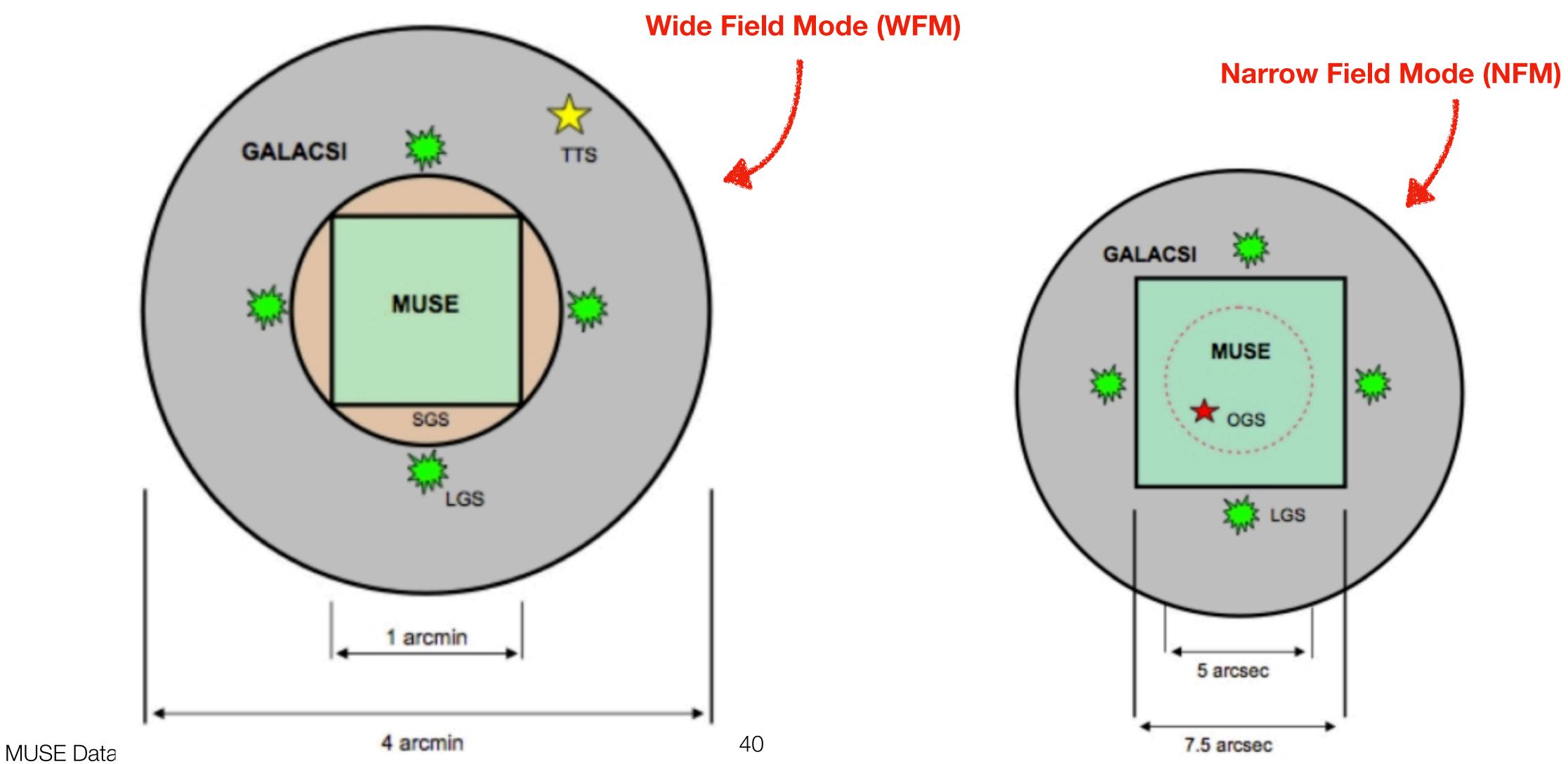
MUSE: Multi-Unit Spectroscopic Explorer Modes

| 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 2 nd 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 |



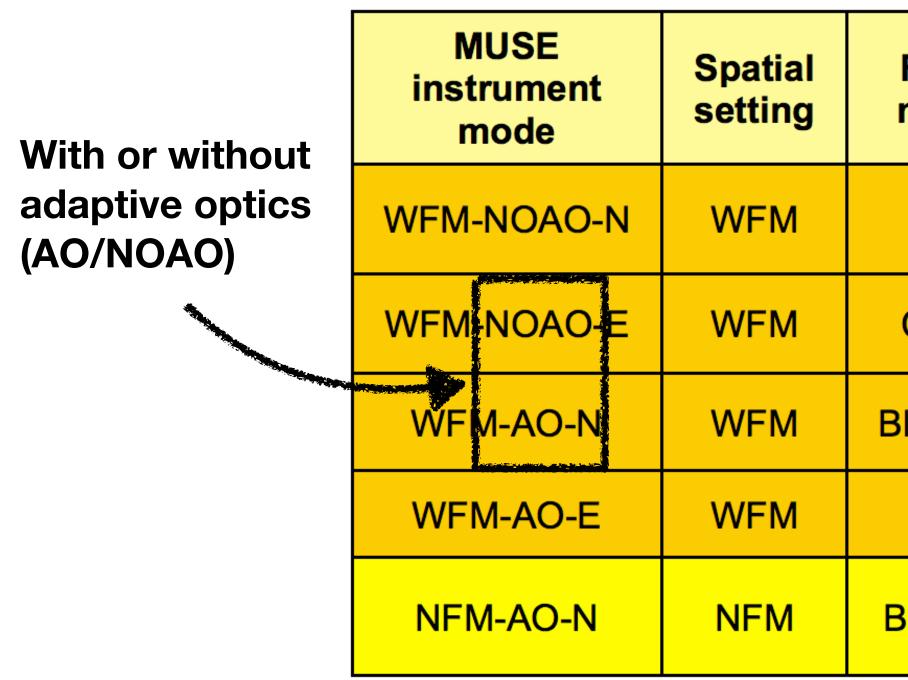
MUSE Data Reduction Workshop, PUC, August 2019

MUSE: Multi-Unit Spectroscopic Explorer Wide Field Mode and Narrow Field Mode





MUSE: Multi-Unit Spectroscopic Explorer Modes



MUSE Data Reduction Workshop, PUC, August 2019

| Filter name | Spectral range (nm) |
|----------------|---|
| Blue | 480-930 |
| Clear | 465-930 ^(*) with 2 nd order contamination at 850-930 nm |
| Blue-Na | 480-582, 597-930 |
| Na | 465-576, 601-930 ^(*) |
| Blue-IR | 480-578, 605-930 Nota: the Na Notch filter is located in GALACSI |

MUSE: Multi-Unit Spectroscopic Explorer AO and NOAO

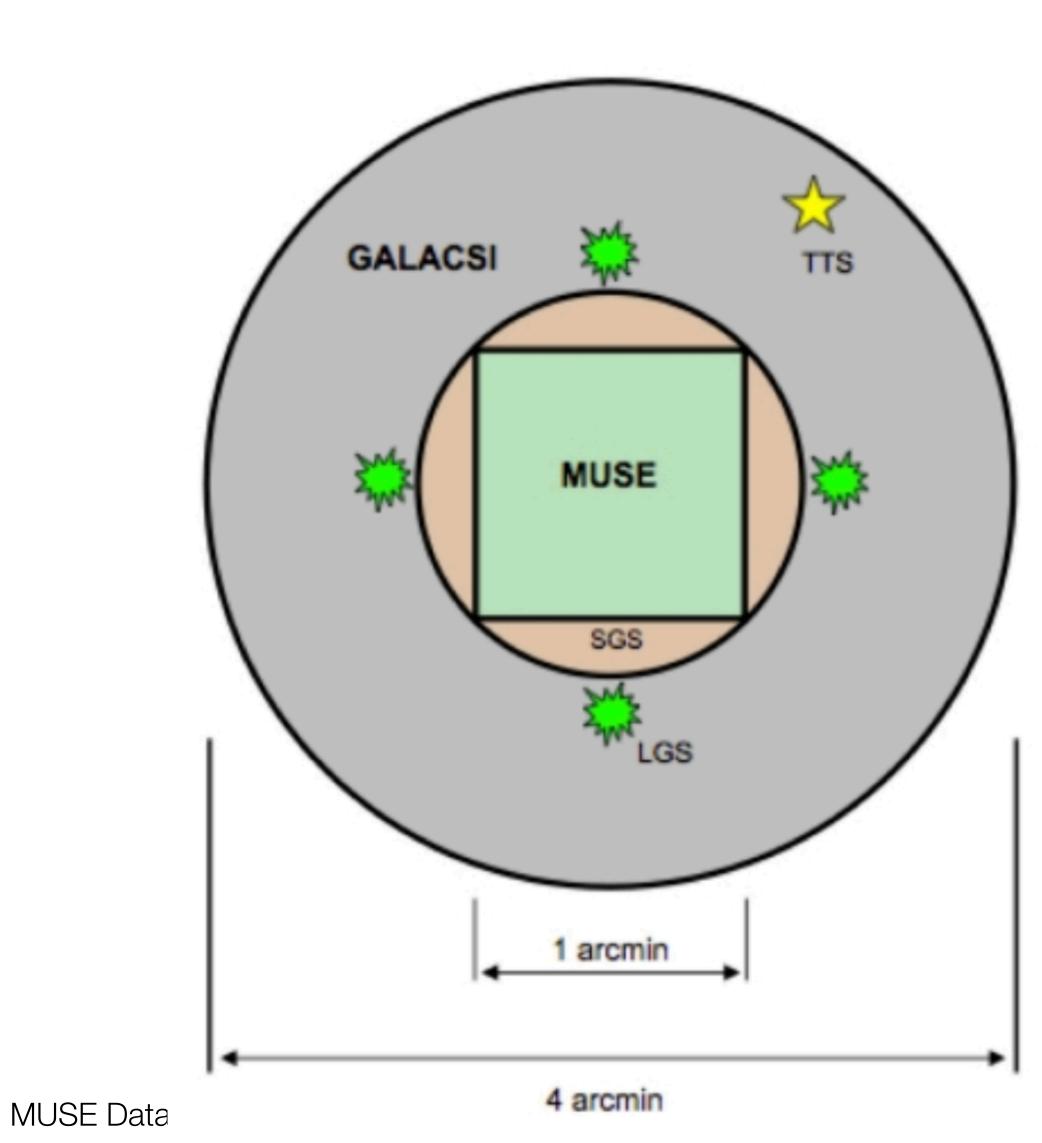
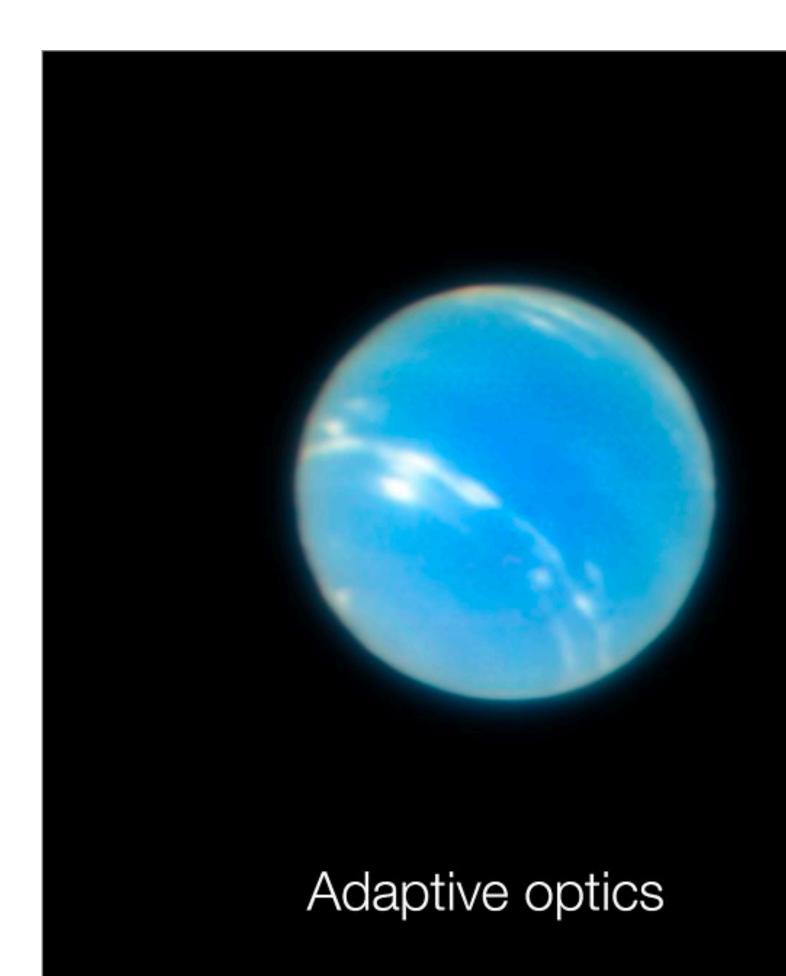




Image credit: Roland Bacon



MUSE: Multi-Unit Spectroscopic Explorer AO and NOAO



MUSE Data Reduction Workshop, PUC, August 2019

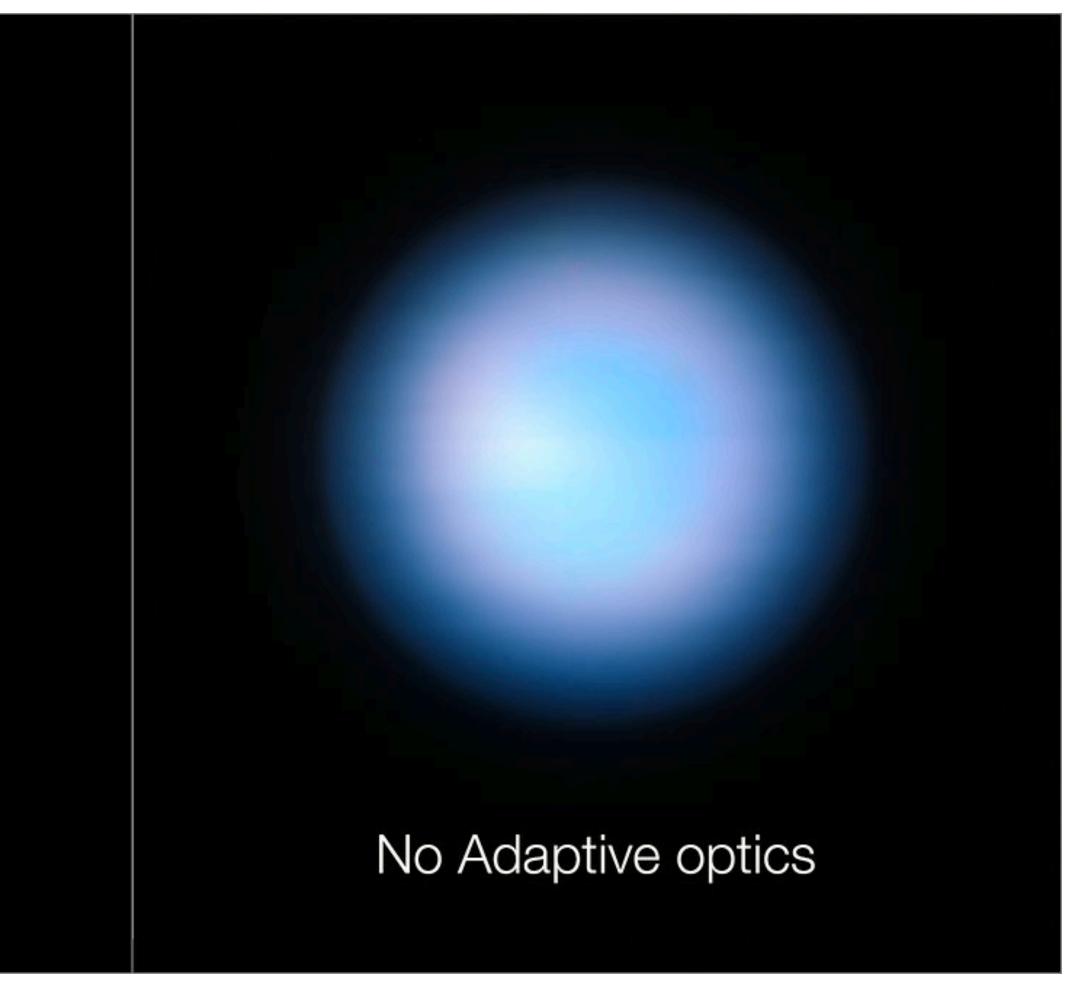


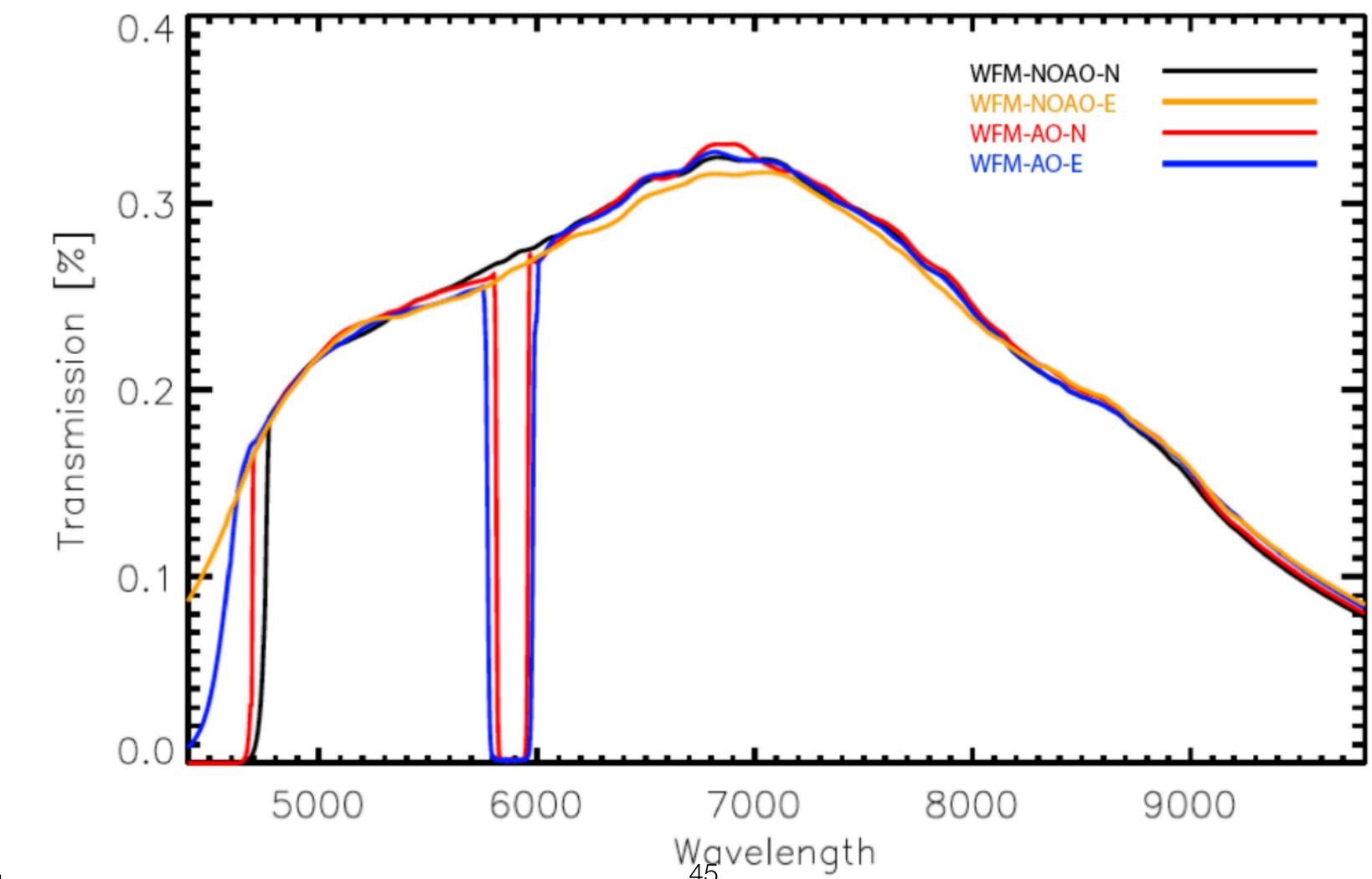
Image credit: ESO/P. Weilbacher (AIP)

MUSE: Multi-Unit Spectroscopic Explorer Modes

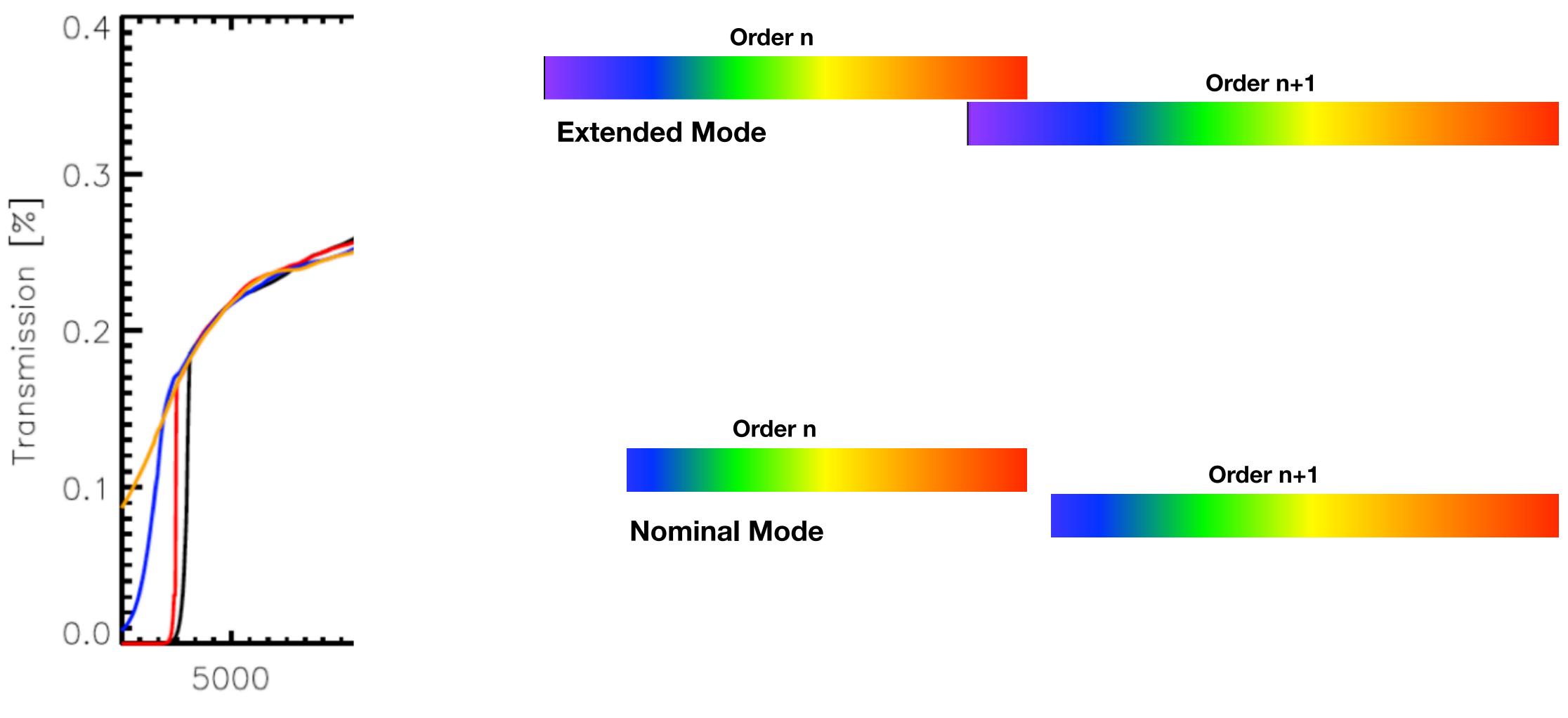
| MUSE instrument mode | Spatial setting | Filter name | Spectral range (nm) | | | |
|-----------------------------------|-----------------|----------------|---|--|--|--|
| WFM-NOAO-N | WFM | Blue | 480-930 | | | |
| WFM-NOAO-E | WFM | Clear | 465-930 ^(*) with 2 nd order contamination at 850-930 nm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

MUSE Data Reduction Workshop, PUC, August 2019

MUSE: Multi-Unit Spectroscopic Explorer Extended and Nominal modes



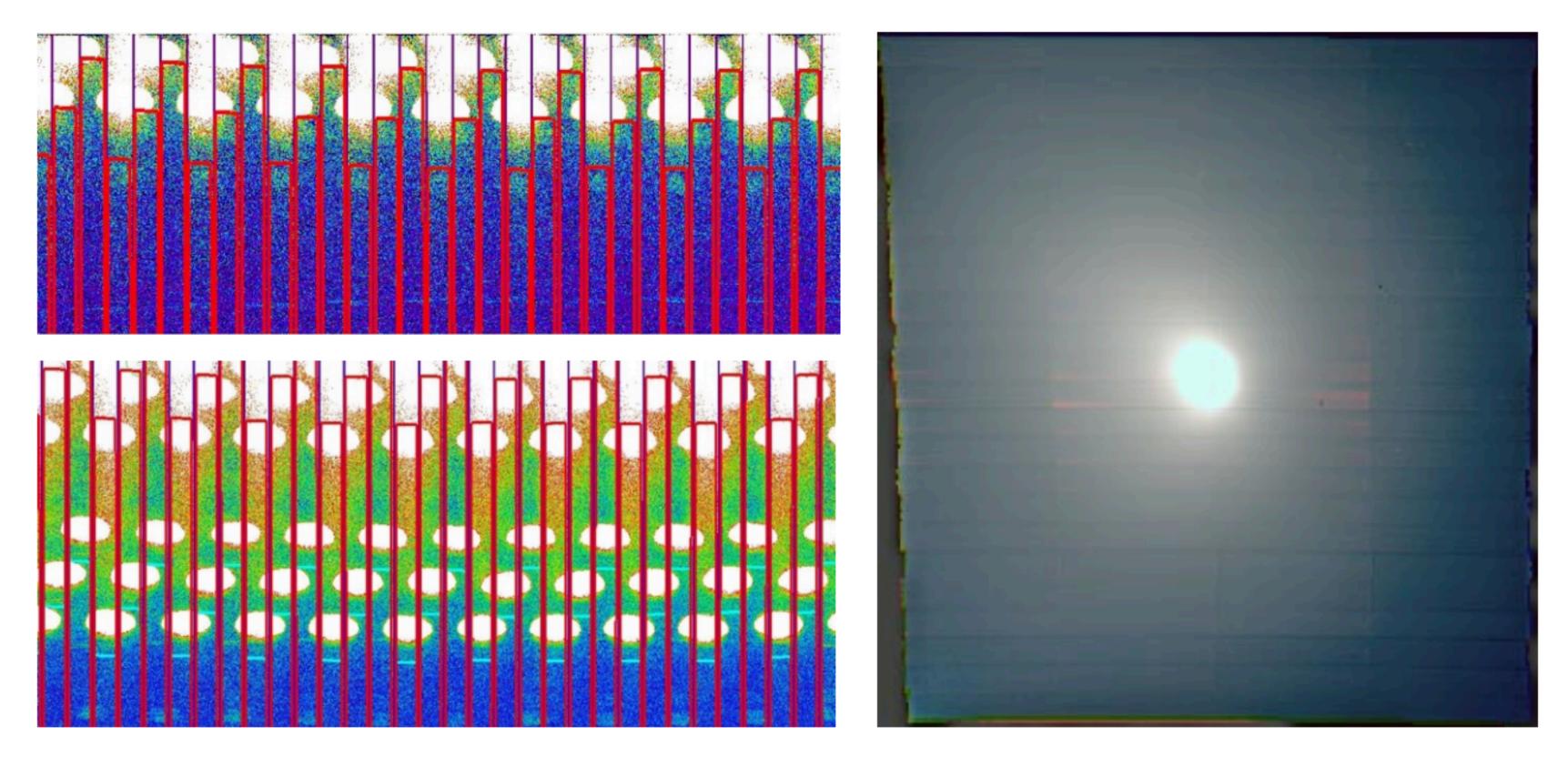
MUSE: Multi-Unit Spectroscopic Explorer Extended and Nominal modes



MUSE: Multi-Unit Spectroscopic Explorer Wide Field Mode and Narrow Field Mode

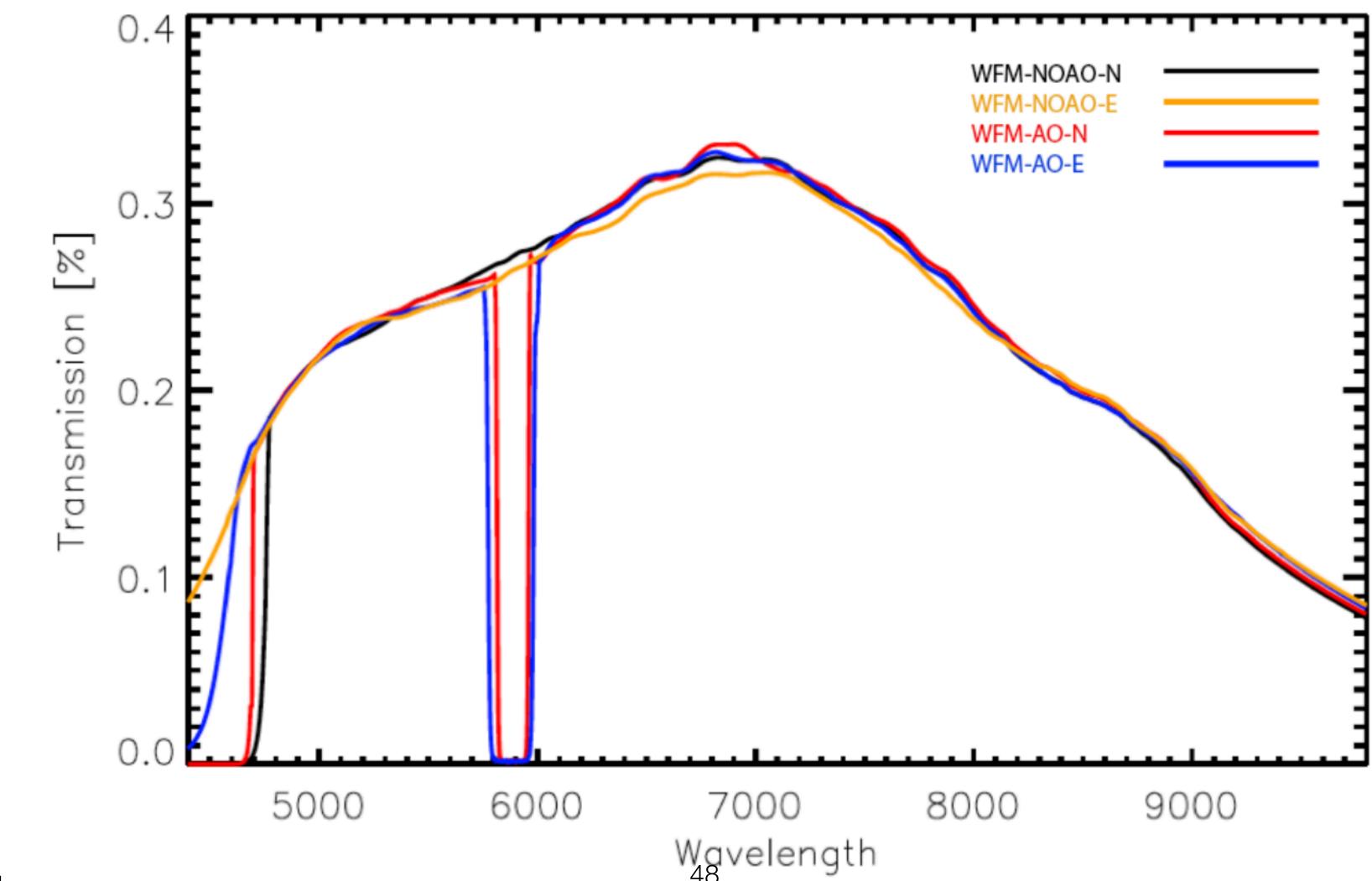
Nominal Mode

Extended Mode



MUSE Data Reduction Workshop, PUC, August 2019

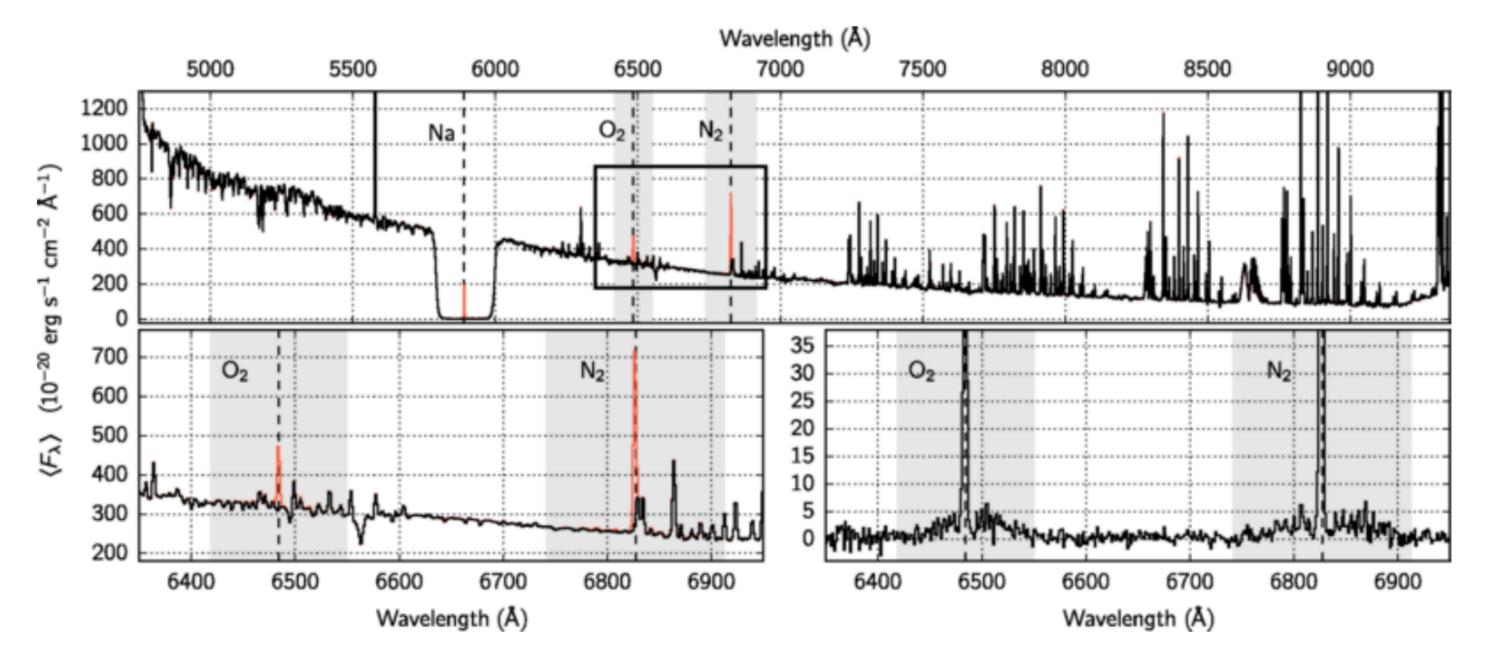
MUSE: Multi-Unit Spectroscopic Explorer Extended and Nominal modes



MUSE: Multi-Unit Spectroscopic Explorer Raman Lines

Table 7 Raman Lines

| Raman | λ algsf | CO ₂ | CO ₂ | 02 | N2 | CH4 | O 2 | H ₂ O | N2 |
|--------------|---------------------|-----------------|-----------------|---------------------|---------------------|---------|---------------|------------------|---------------|
| Line | | | | (V1←0) | (V1←0) | | (V2←0) | | (V2←0) |
| Raman | | 1285.8 | 1388.1 | 1556.4 | 2330.7 | 2914.2 | 3089.2 | 3651.7 | 4631.2 |
| shift (cm-1) | | | | | | | | | |
| 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 |



1 - 7

MUSE Data Reduction W

| S | visible | with | MUSE | with | laser (| on. |
|---|---------|------|------|------|---------|-----|
|---|---------|------|------|------|---------|-----|

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

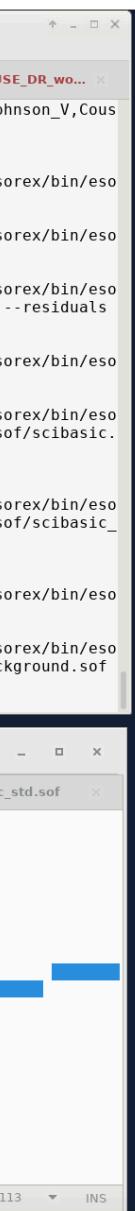
ESO Pipelines ESOrex and ESO Reflex

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

| Terminal - ejo File Edit View Terminal Tabs Help | ohnston@horus:/data2/MUSE_DR_workshop2 | |
|--|--|--|
| | ohnston@horus:/data2/MUSE_DR_wo × ejohnston@horus:/data | a2/MUS |
| <pre>ins_R,Cousins_I,SDSS_u,SDSS_g,SDSS_r,SDSS nohup: ignoring input and appending outpu [ejohnston@horus MUSE_DR_workshop2]\$ OMP_ rexlog-file=log/bias.logoutput-dir= nohup: ignoring input and appending outpu [ejohnston@horus MUSE_DR_workshop2]\$ OMP_ rexlog-file=log/flat.logoutput-dir= nohup: ignoring input and appending outpu [ejohnston@horus MUSE_DR_workshop2]\$ OMP_ rexlog-file=log/wavecal.logoutput-d sof/wave.sof nohup: ignoring input and appending outpu [ejohnston@horus MUSE_DR_workshop2]\$ OMP_ rexlog-file=log/skyflat.logoutput-d sof/wave.sof nohup: ignoring input and appending outpu [ejohnston@horus MUSE_DR_workshop2]\$ OMP_ rexlog-file=log/skyflat.logoutput-d nohup: ignoring input and appending outpu [ejohnston@horus MUSE_DR_workshop2]\$ OMP_ rexlog-file=log/scibasic.logoutput- sof nohup: ignoring input and appending outpu [ejohnston@horus MUSE_DR_workshop2]\$ OMP_ rexlog-file=log/scibasic_std.logoutput- sof nohup: ignoring input and appending outpu [ejohnston@horus MUSE_DR_workshop2]\$ OMP_ rexlog-file=log/scibasic_std.logoutput- std.sof nohup: ignoring input and appending outpu [ejohnston@horus MUSE_DR_workshop2]\$ OMP_ rexlog-file=log/std.logoutput-dir=p nohup: ignoring input and appending outpu [ejohnston@horus MUSE_DR_workshop2]\$ OMP_</pre> | <pre>it to 'nohup.out' ./MUSE_DR_workshop2 NUM_THREADS=24 nohup taskset -c 0-23 /raid/ejohnsto products/ muse_biasmergenifu=-1 sof/bias.sof it to 'nohup.out' NUM_THREADS=24 nohup taskset -c 0-23 /raid/ejohnsto products/ muse_flatmergenifu=-1 sof/flat.sof it to 'nohup.out' NUM_THREADS=24 nohup taskset -c 0-23 /raid/ejohnsto ir=products/ muse_wavecalmergenifu=-1resam it to 'nohup.out' NUM_THREADS=24 nohup taskset -c 0-23 /raid/ejohnsto ir=products/ muse_twilight sof/skyflat.sof it to 'nohup.out' NUM_THREADS=24 nohup taskset -c 0-23 /raid/ejohnsto dir=products/science/ muse_scibasicnifu=-1mer it to 'nohup.out' NUM_THREADS=24 nohup taskset -c 0-23 /raid/ejohnsto dir=products/science/ muse_scibasicnifu=-1mer it to 'nohup.out' NUM_THREADS=24 nohup taskset -c 0-23 /raid/ejohnsto put-dir=products/std/ muse_scibasicnifu=-1mer it to 'nohup.out' NUM_THREADS=24 nohup taskset -c 0-23 /raid/ejohnsto put-dir=products/std/ muse_scibasicnifu=-1mer it to 'nohup.out' NUM_THREADS=24 nohup taskset -c 0-23 /raid/ejohnsto put-dir=products/std/ muse_scibasicnifu=-1mer it to 'nohup.out' NUM_THREADS=24 nohup taskset -c 0-23 /raid/ejohnsto products/std/ muse_standardfilter=white sof/std.s it to 'nohup.out' NUM_THREADS=24 nohup taskset -c 0-23 /raid/ejohnsto products/std/ muse_standardfilter=white sof/std.s it to 'nohup.out' NUM_THREADS=24 nohup taskset -c 0-23 /raid/ejohnsto products/std/ muse_standardfilter=white sof/std.s</pre> | on/Esc on/Esc on/Esc on/Esc on/Esc on/Esc on/Esc on/Esc on/Esc |
| Open 💌 🕞 | scibasic.sof Save | |
| MUSE.2016-10-08T02:56:18.752.xml × | /data2/MUSE_DR_workshop2/sof | ibasic |
| <pre>raw/M.MUSE.2015-06-24T08:20:55.820.fits raw/M.MUSE.2015-10-23T12:39:46.396.fits GEOME products/TWILIGHT_CUBE.fits TWILIGHT_CUBE products/MASTER_BIAS.fits MASTER_BIAS products/MASTER_FLAT.fits MASTER_FLAT products/TRACE_TABLE.fits TRACE_TABLE products/WAVECAL_TABLE.fits WAVECAL_TABLE raw/MUSE.2016-10-08T02:35:30.013.fits.fz raw/MUSE.2016-10-08T02:56:18.752.fits.fz</pre> | BADPIX_TABLE TRY_TABLE SKY WFM-NOAO-N 11.71 0.0000 ILLUM WFM-NOAO-N 11.73 0.0000 OBJECT WFM-NOAO-N 11.82 0.0000 | 9 |
| raw/MUSE.2016-10-08T03:07:05.640.fits.fz | OBJECT WFM-NOAO-N 11.83 90.000 | 0. col 1 |
| | | A 45 1 7 1 |



ESO Data Reduction Pipelines ESO Reflex

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



| ta: Is"-> "Animate at Runtime" to start the workflow. appropriate. | Input: • ROOT_DATA_DIR: ROOT_DATA_PATH_TO_REPLACE/ • RAW_DATA_DIR: \$ROOT_DATA_DIR/reflex_input/muse Only change CALB_DATA_DIR if you do NOT want to use the calibration data delivered with the pipeline: • CAUB_DATA_DIR: CAUB_DATA_PATH_TO_REPLACE/muse-1.1/ | RecipeFailureMode: Ask | Global parameter for the behaviour when a recipe fails. 'Ask' means that each time a recipe fails, the choice to continue or stop wil be presented. 'Continue' means that the workflow will ignore errors and continue. 'Stop' means the workflow will stop. |
|---|--|--|--|
| Is"-> "Animate at Runtime" to start the workflow. | RAW_DATA_DIR: \$ROOT_DATA_DIR/reflex_input/muse Only change CALIB_DATA_DIR if you do NOT want to use the calibration data delivered with the pipeline: | | 'Ask' means that each time a recipe fails, the choice to continue or stop wil be presented. 'Continue' means that the workflow will ignore errors and continue. |
| to start the workflow. | Only change CAUB_DATA_DIR if you do NOT want to use the calibration data delivered with the pipeline: | | presented. 'Continue' means that the workflow will ignore errors and continue. |
| | calibration data delivered with the pipeline: | | |
| | calibration data delivered with the pipeline: | | "Stop" means the workflow will stop. |
| appropriate. | CAUS DATA DE- CAUS DATA PATH TO REPLACE/muse-1.1/ | | |
| appropriate. | CADE DATA DR. CADE DATA PATH TO REPORCEMBLE TIT | EraseDirs: false | Change "EraseDirs" to true' to erase BOOKKEEPING DIR, TMP PRODUCTS DIR and LOGS DIR each time the workflow |
| R will be searched for data. | Output: | | is run (Lazy Mode will not work anymore). |
| DIR. | | FITS VIEWER deg | fits viewer to use for the inspection of input/output products |
| t will be searched for raw | | • | ha we we to use for the trapectori of highly output products |
| | Working Directories: | GlobalPlotInteractivity: true | Disable interactive GUIs for the whole workflow |
| to start the workflow. | BOOKKEEPING_DIR: \$ROOT_DATA_DIR/reflex_book_keeping/muse | | Overrides in subworkflows have precedence. |
| escribed in | LOGS_DIR: \$ROOT_DATA_DIR/reflex_logs/muse | SelectDatasetMethod: Interactive | Selection method for the Data Set Chooser |
| | TMP_PRODUCTS_DIR: \$ROOT_DATA_DIR/reflex_tmp_products/muse | | |
| THEX. | BOOKKEEPING_DB: \$BOOKKEEPING_DIR/bookkeeping.db | ProductExplorerMode: Triggered | Enabled - ProductExplorer pops up after each dataset is finished Triggered - ProductExplorer pops up after all datasets are finished Disabled - do no use ProductExplorer |
| | to start the workflow. | Will be searched for raw Working Directories: to start the workflow. BOORREEPING_DIR: \$RDOT_DATA_DIR/reflex_book_keeping/muse eLOGS_DIR: \$RDOT_DATA_DIR/reflex_logs/muse oscribed in credit this paper in flex. TMP_PRODUCTS_DIR: \$RDOT_DATA_DIR/reflex_tmp_products/muse eBOORREEPING_DB: \$RDOT_DATA_DIR/reflex_tmp_products/muse eBOORREEPING_DB: \$RDOTRATA_DIR/reflex_tmp_products/muse | Will be searched for raw Working Directories: •GiobalPlotInteractivity: true to start the workflow. •BOORXEEPING_DIR: \$ROOT_DATA_DIR/reflex_book_keeping/muse •GiobalPlotInteractivity: true escribed in •LOGS_DIR: \$ROOT_DATA_DIR/reflex_logs/muse •SelectDatasetMethod: interactive redit this paper in flex. •TMP_PRODUCTS_DIR: \$ROOT_DATA_DIR/reflex_tmp_products/muse •SelectDatasetMethod: interactive |



LamMin: 4000

Wavelength range of the reconstructed cui

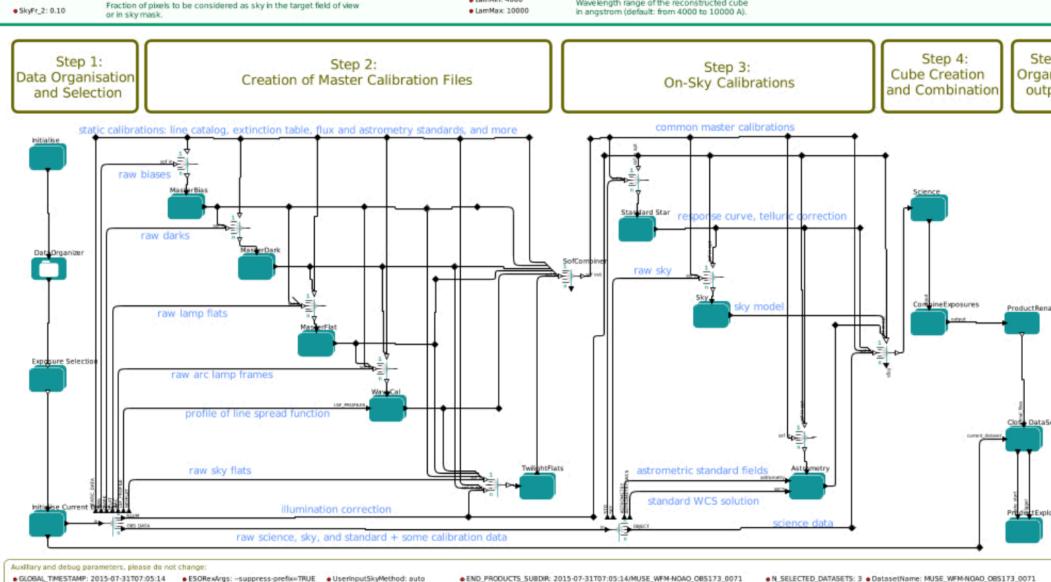


Image credit: MUSE user manual

DDF Director

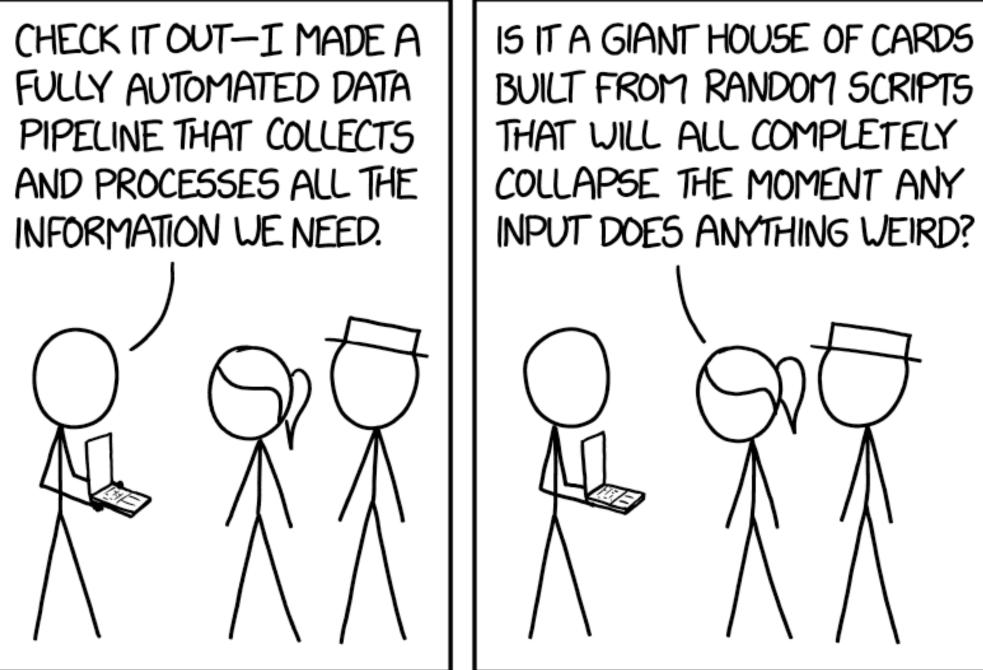
SkyFr_1: 0.85

| wil be | |
|------------------------------|--|
| workflow | |
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| ep 5: nizing puts | |

ESO Data Reduction Pipelines ESOrex or ESO Reflex

• This workshop will focus on **ESOrex**

My personal opinion/experience of using ESO Reflex:



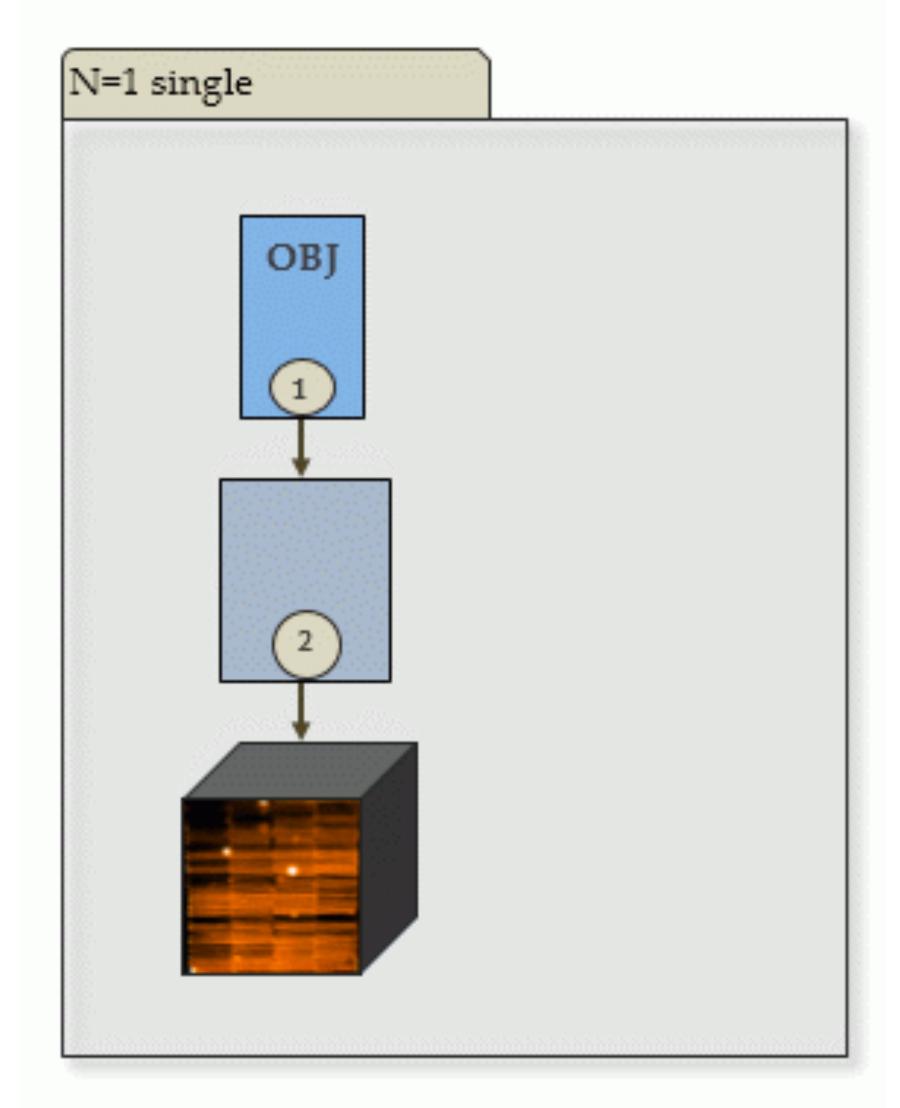




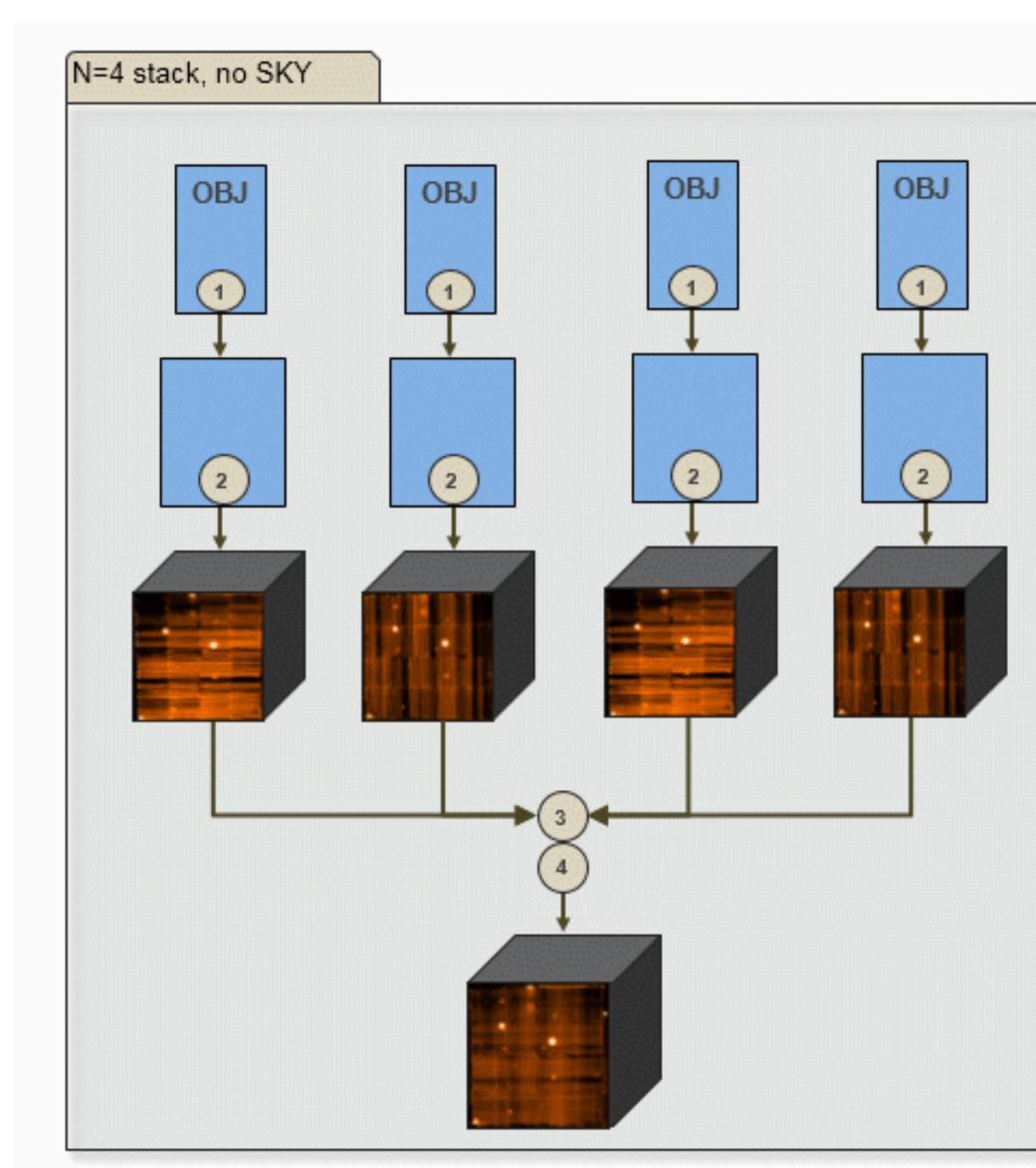


MUSE Data Reduction with ESOrex

MUSE Data Reduction Observing Strategy



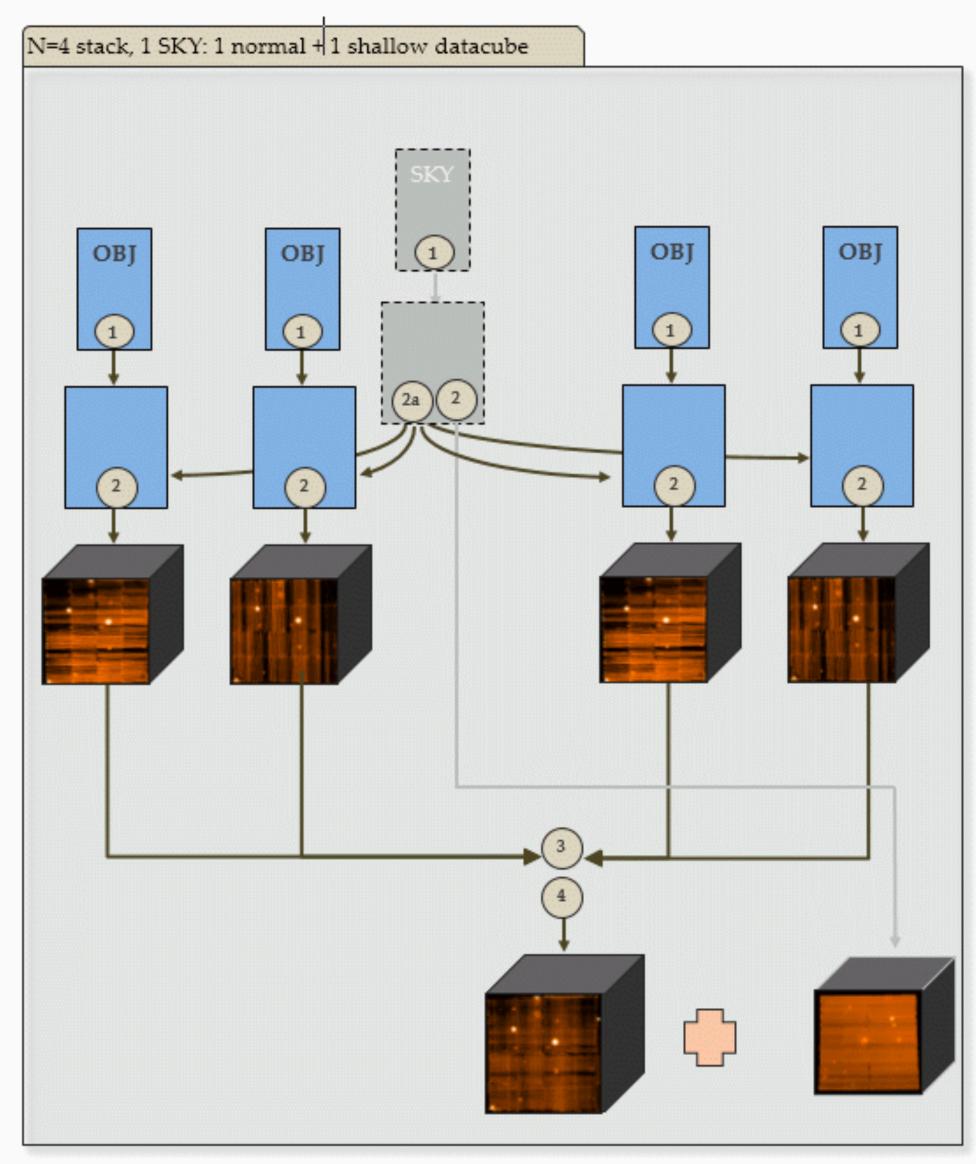
MUSE Data Reduction Workshop, PUC, August 2019

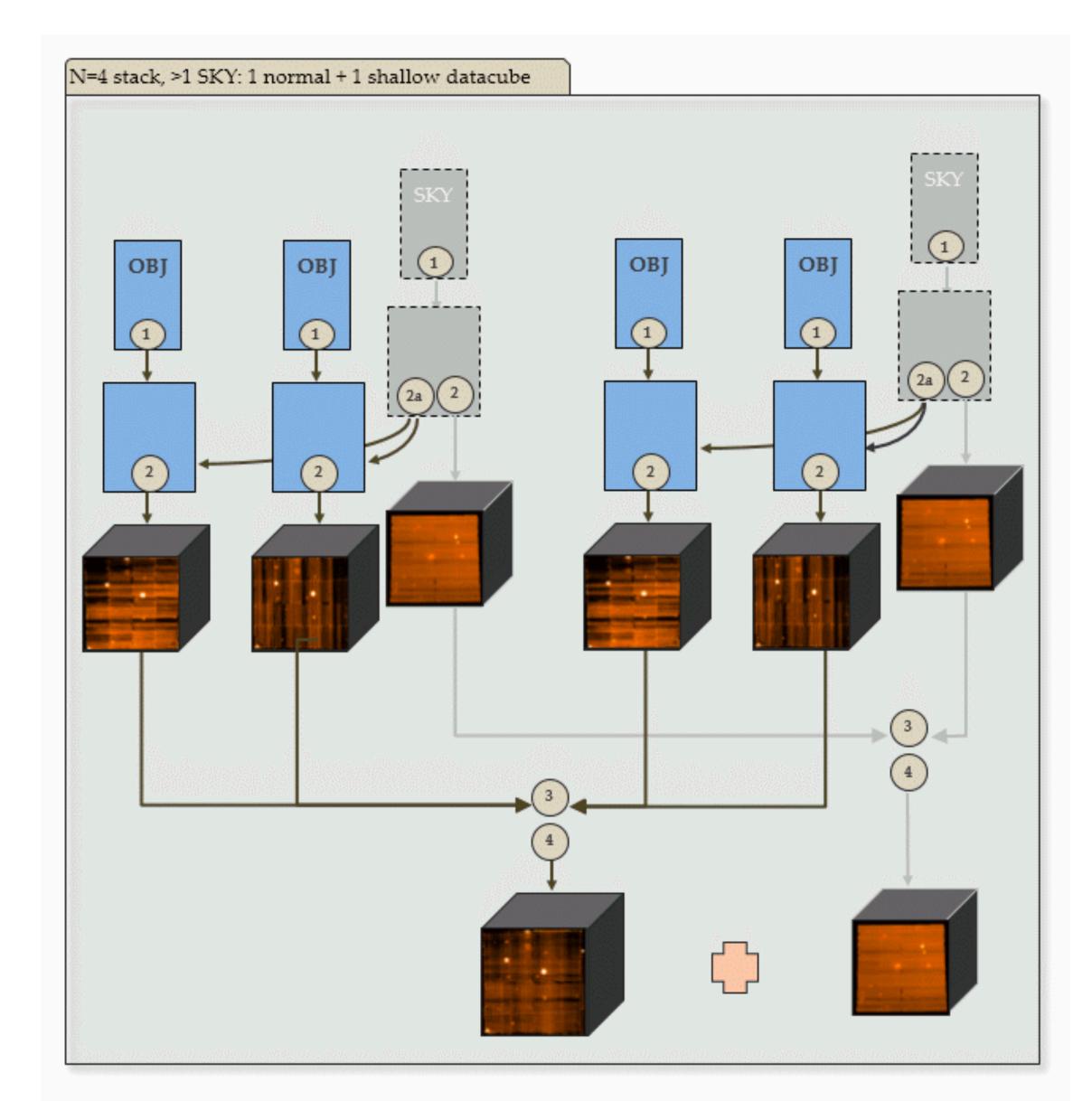


55



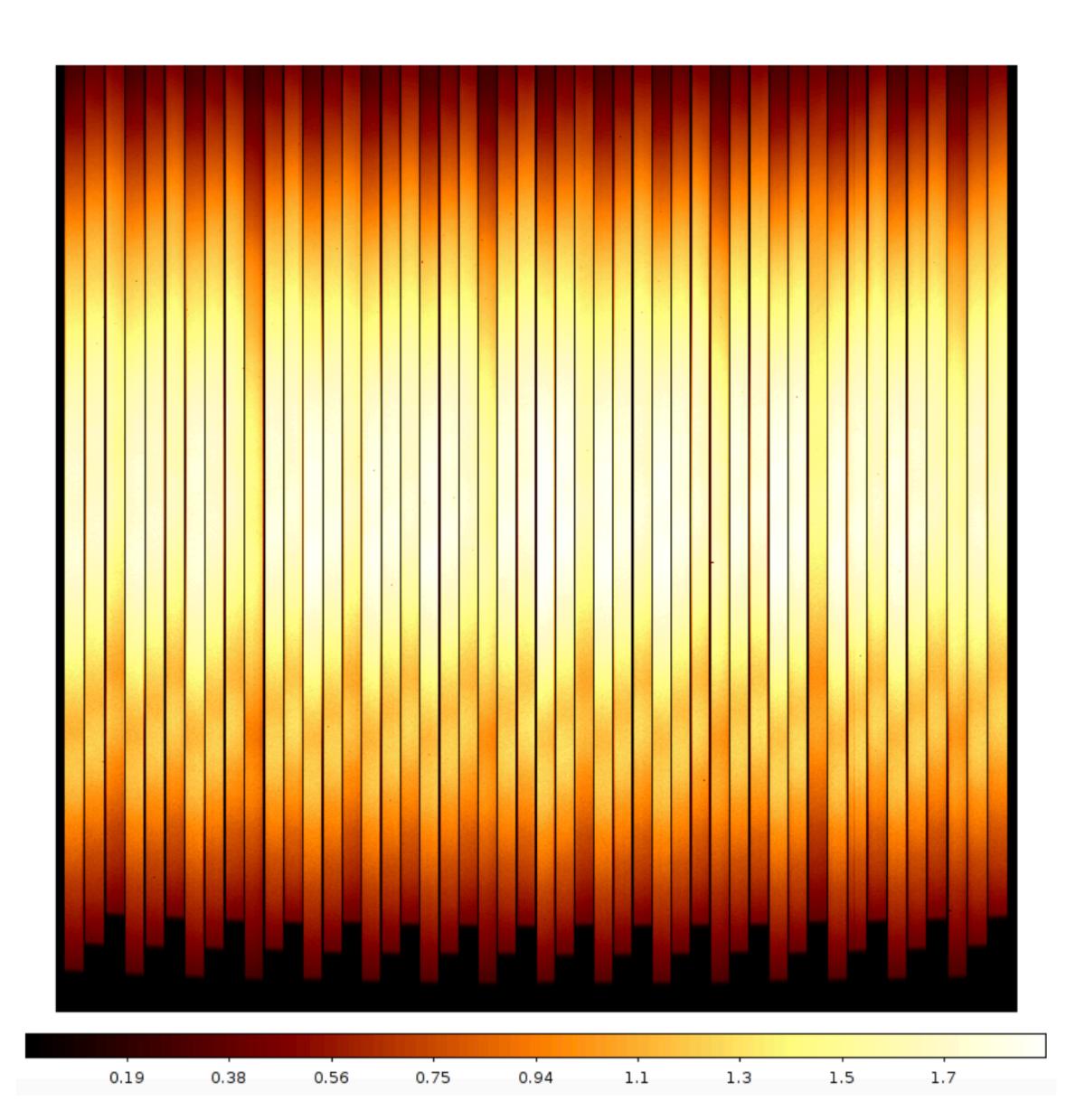
MUSE Data Reduction Observing Strategy





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 \bullet
- Solution-lamp illumination calibrations, \bullet which are taken every hour or when the temperature within the instrument has changed significantly

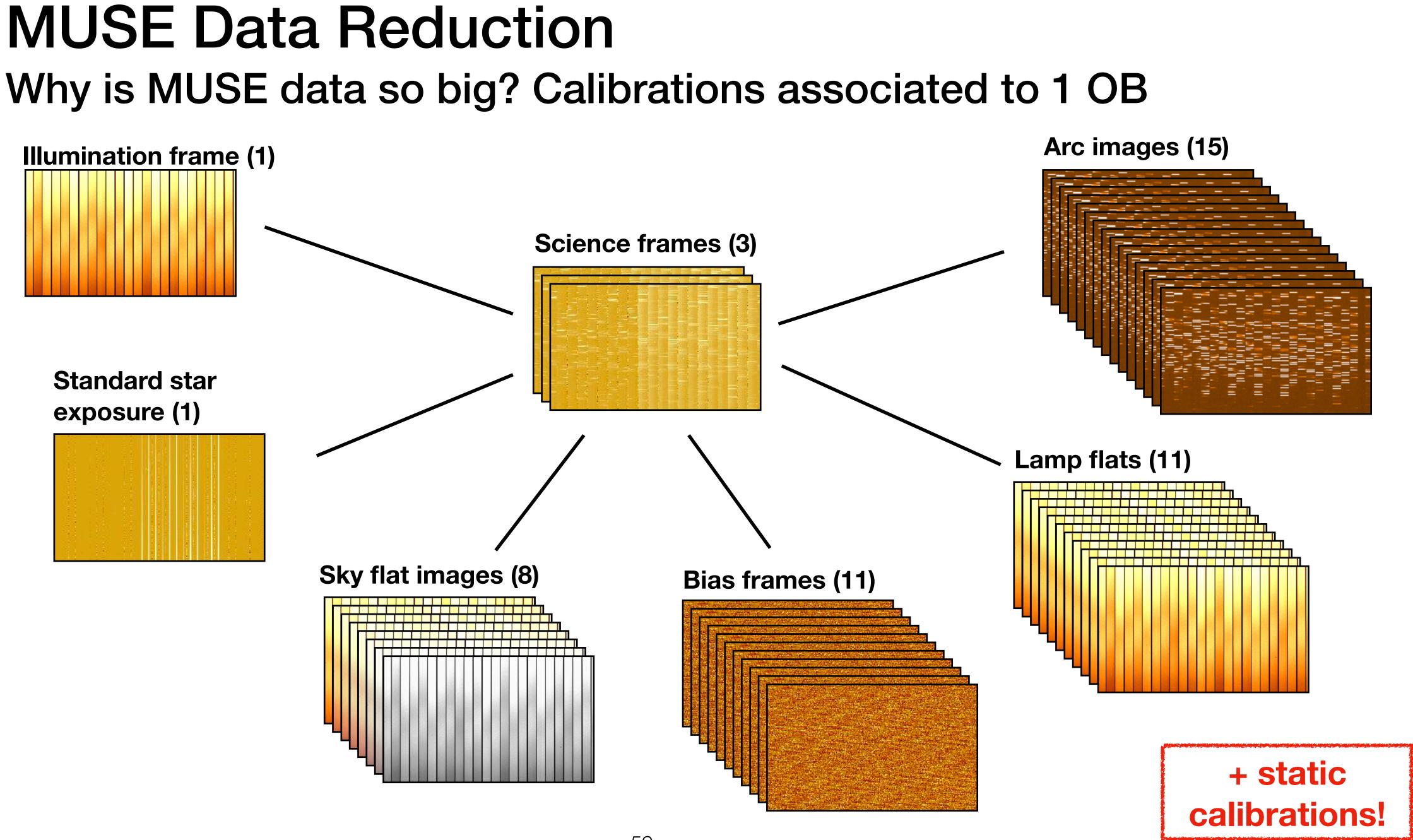


MUSE Data Reduction Computing Power

- MUSE data is **BIG**, Science data and 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

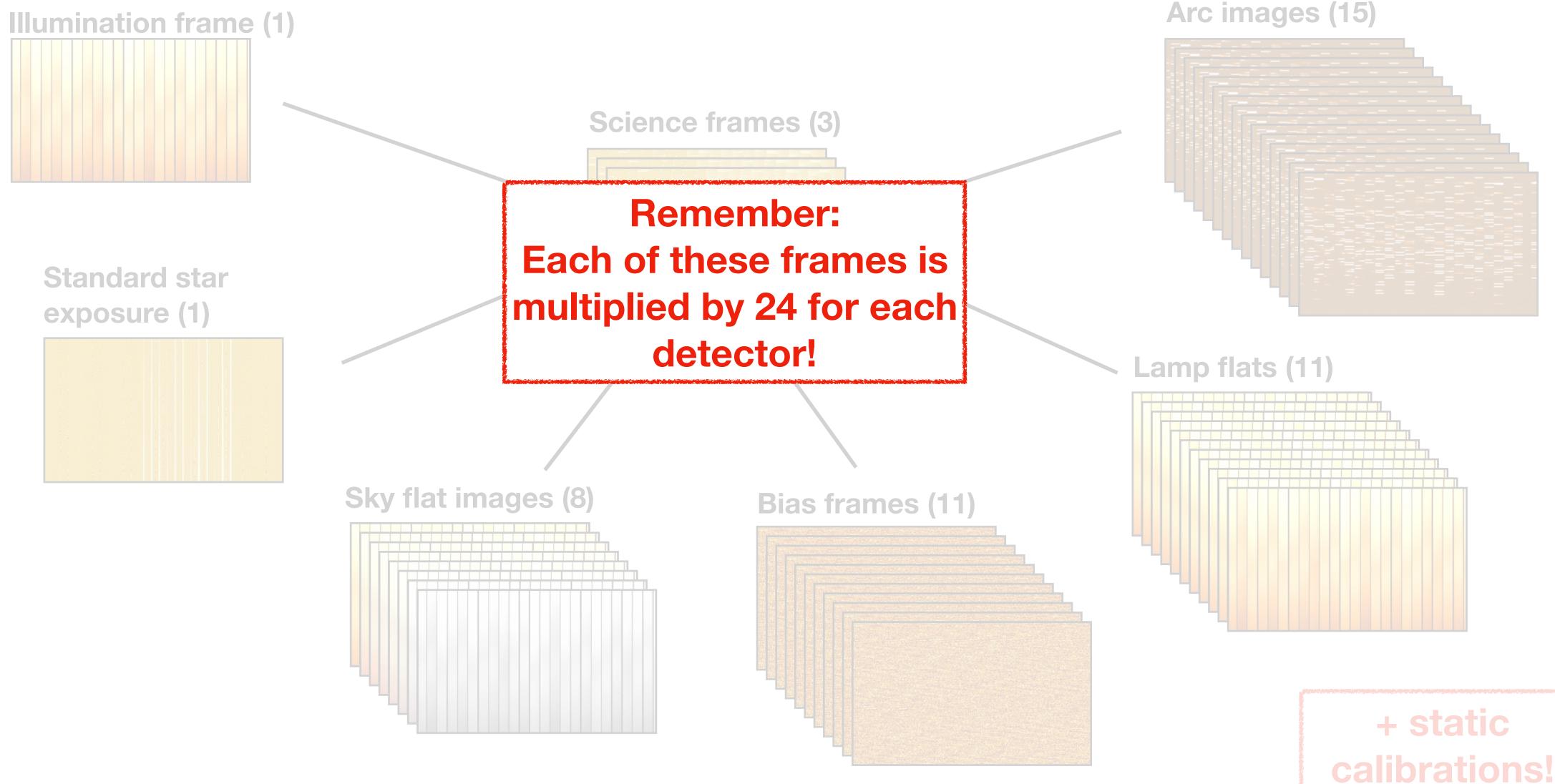
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MUSE data is **BIG**, Science data and calibrations for 1 OB can come to ~20-50GB, and



MUSE Data Reduction Workshop, PUC, August 2019

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



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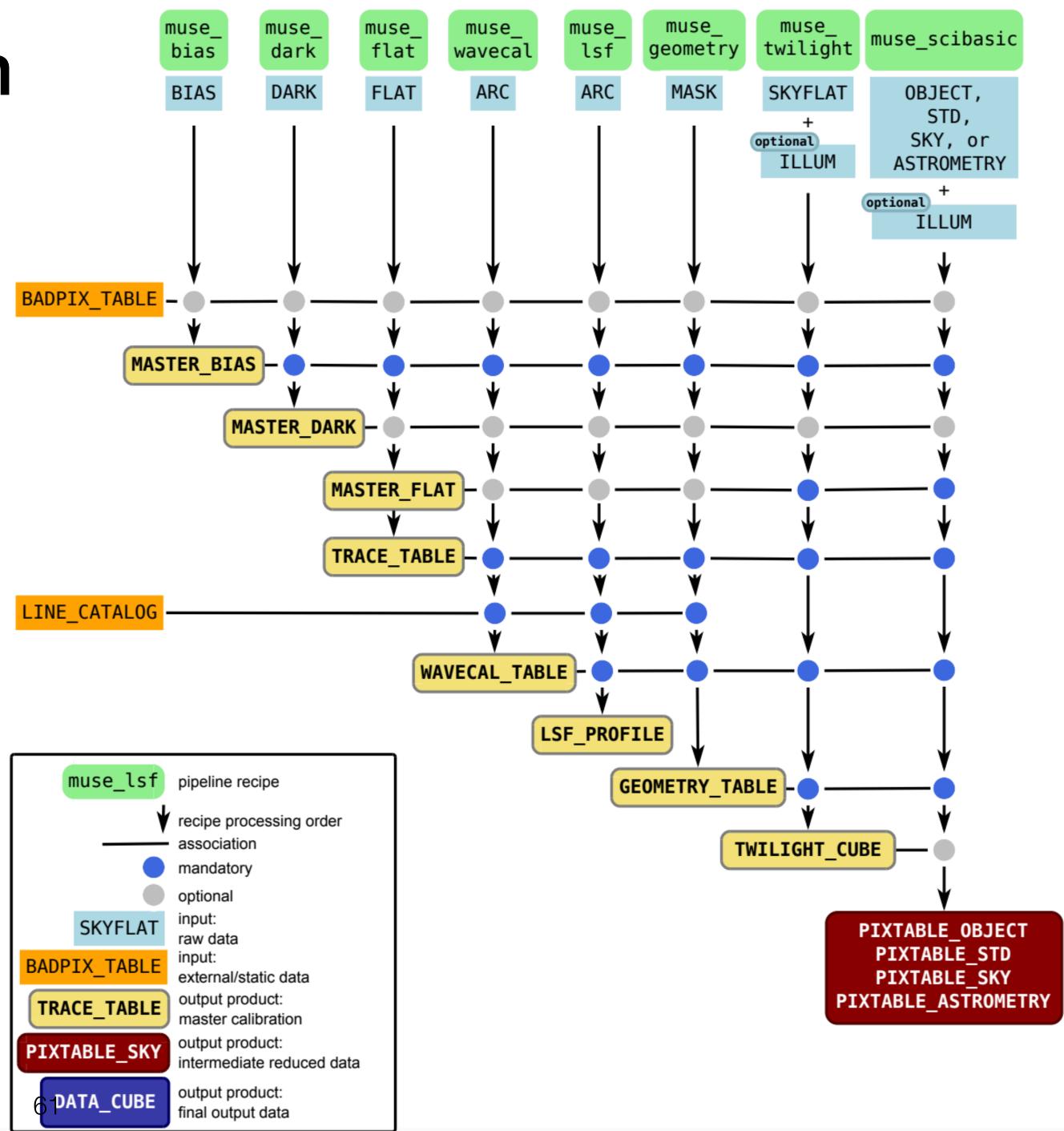
Arc images (15)





MUSE Data Reduction Pre-processing

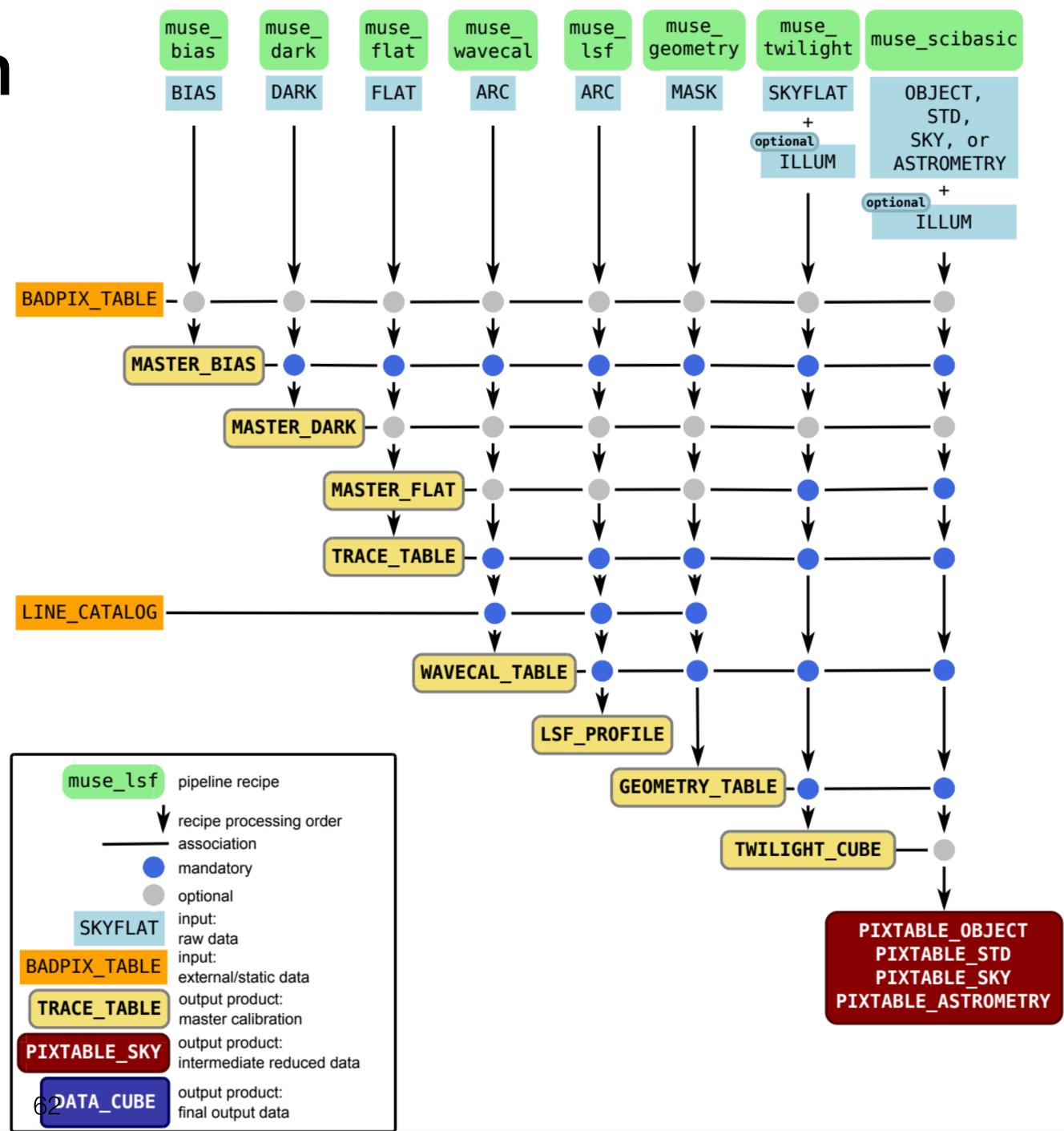
- Basic DR steps
 - muse_bias
 - muse_dark \bullet
 - muse_flat
 - muse_wavecal
 - muse_lsf lacksquare
 - muse_geometry
 - muse_twilight
 - muse_scibasic



MUSE Data Reduction Pre-processing

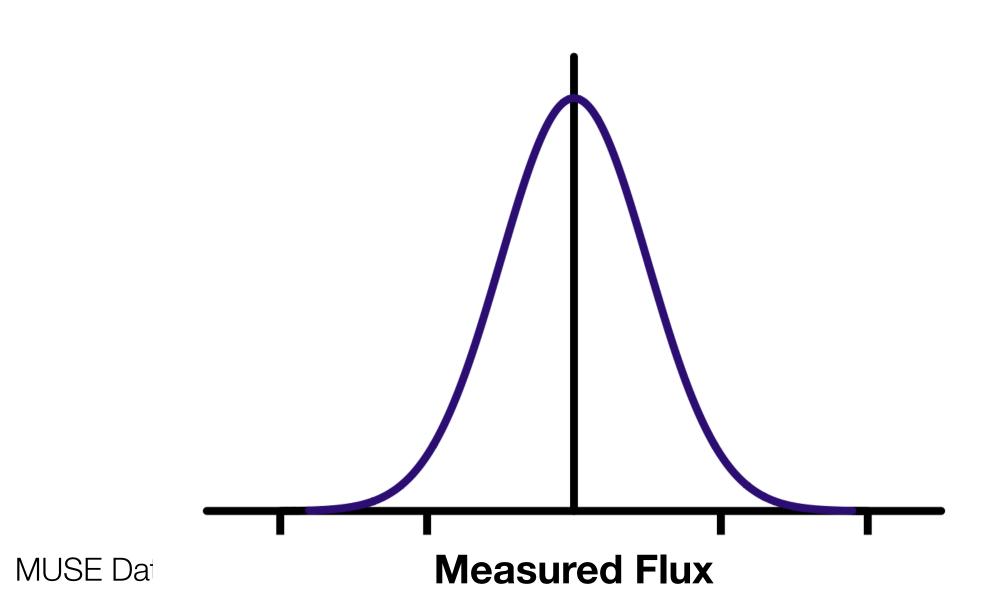
- Basic DR steps \bullet
 - muse_bias
 - muse_dark
 - muse_flat
 - muse_wavecal
 - muse lsf
 - muse_geometry
 - muse_twilight ${\color{black}\bullet}$
 - muse_scibasic

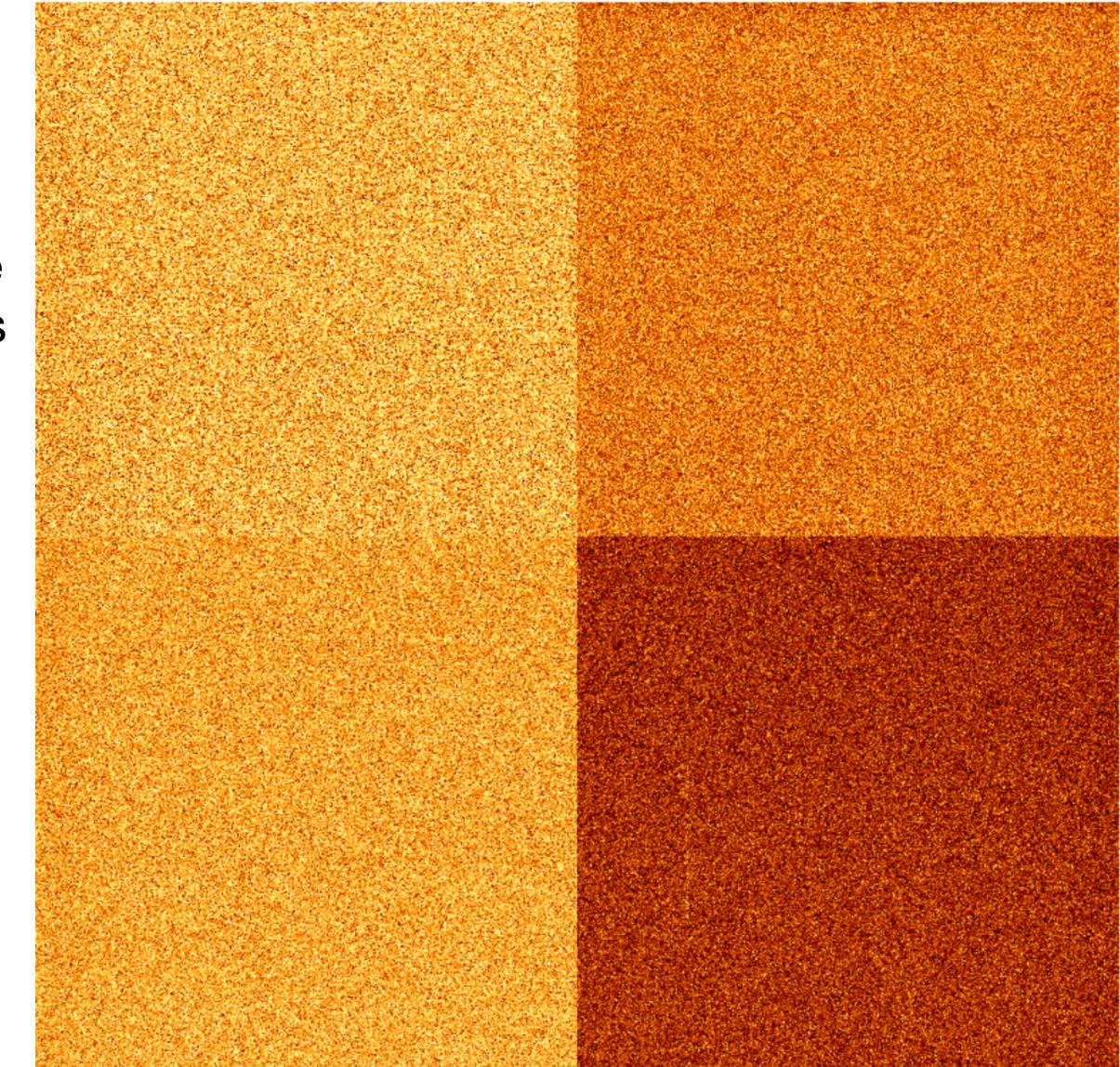
MUSE Data Reduction Workshop, PUC, August 2019



MUSE Data Reduction muse_bias

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

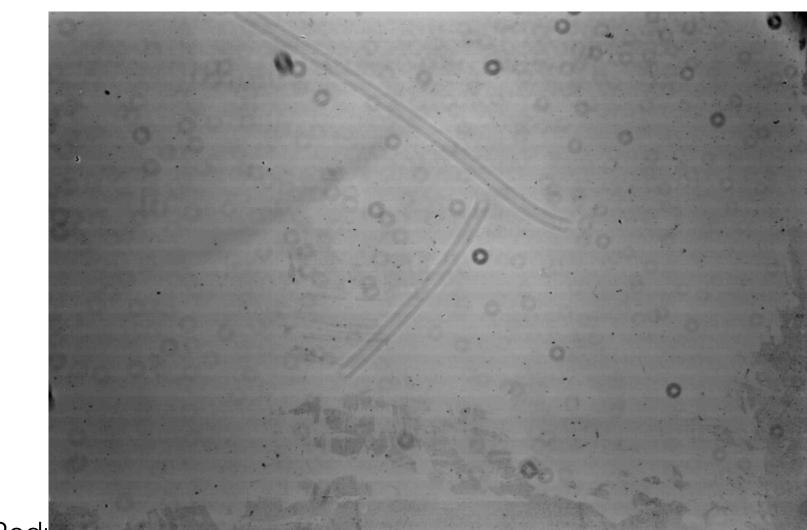




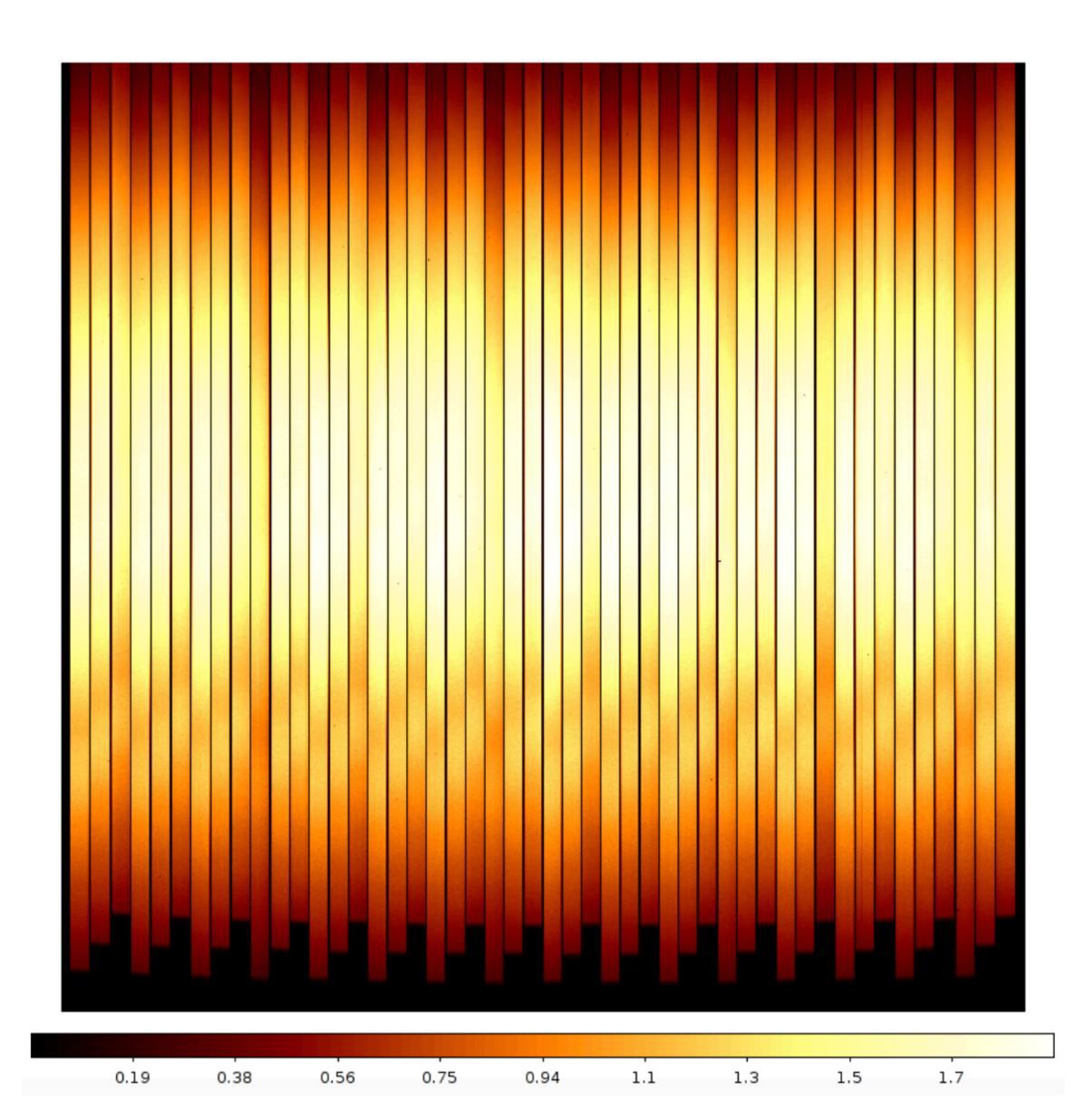
MUSE Data Reduction muse_flat

Creates the Master Flat Field/Trace Table ${\color{black}\bullet}$

- 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 \bullet for each slitlet



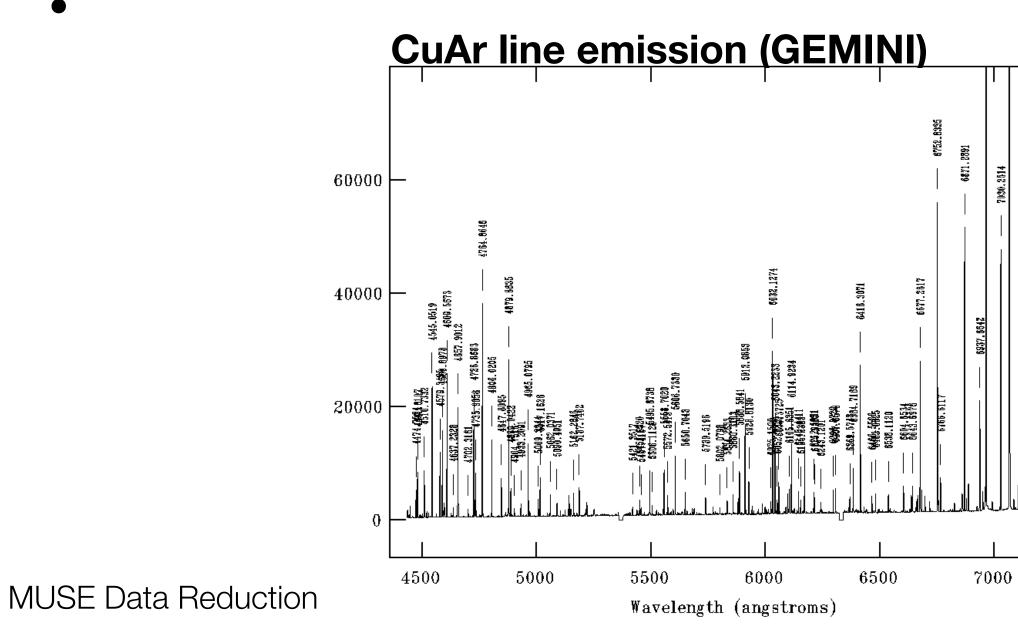
MUSE Data Reduction workshop, PUC, August 2019

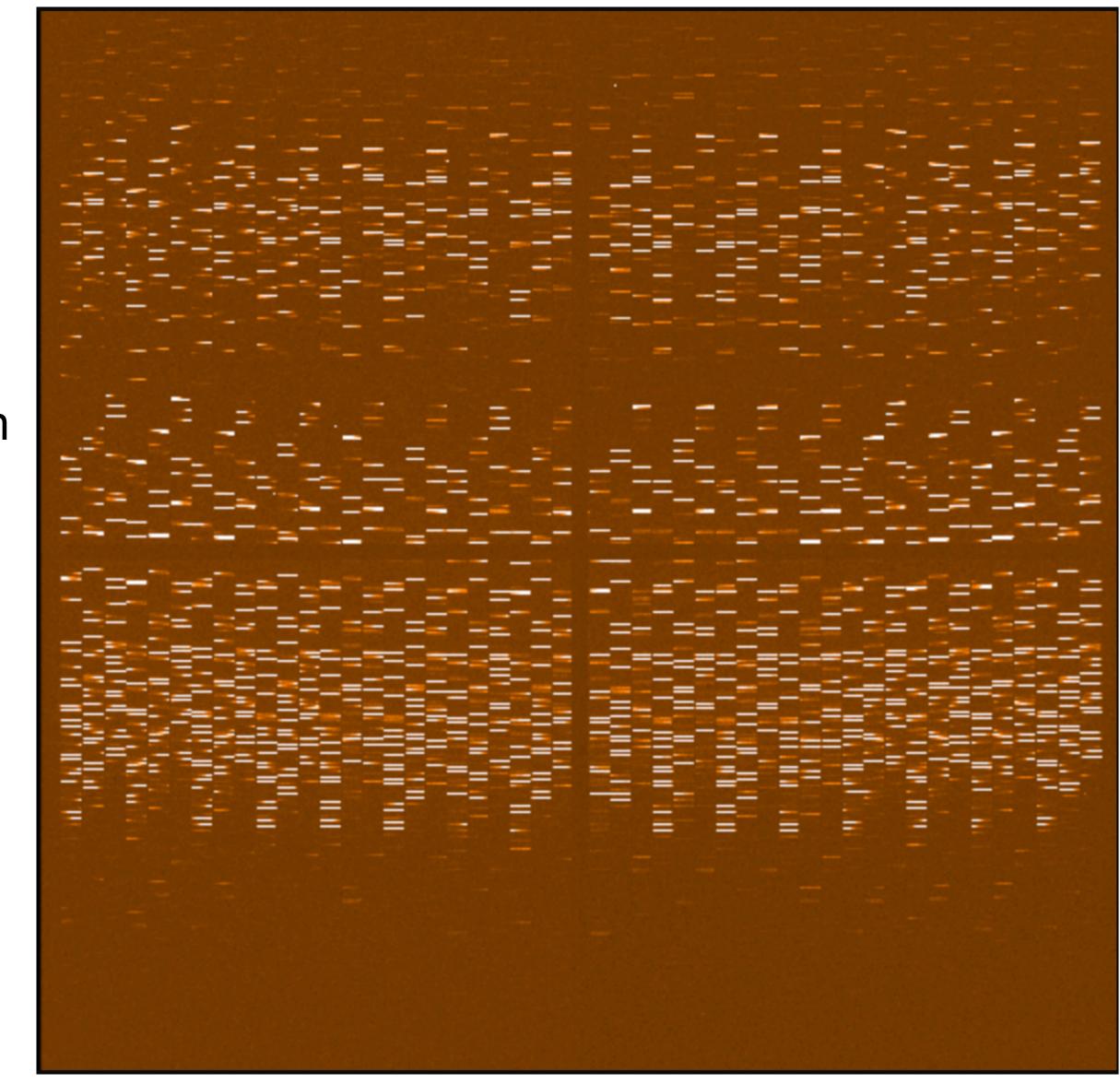


MUSE Data Reduction muse_wavecal

Creates the Wavelength Calibration

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

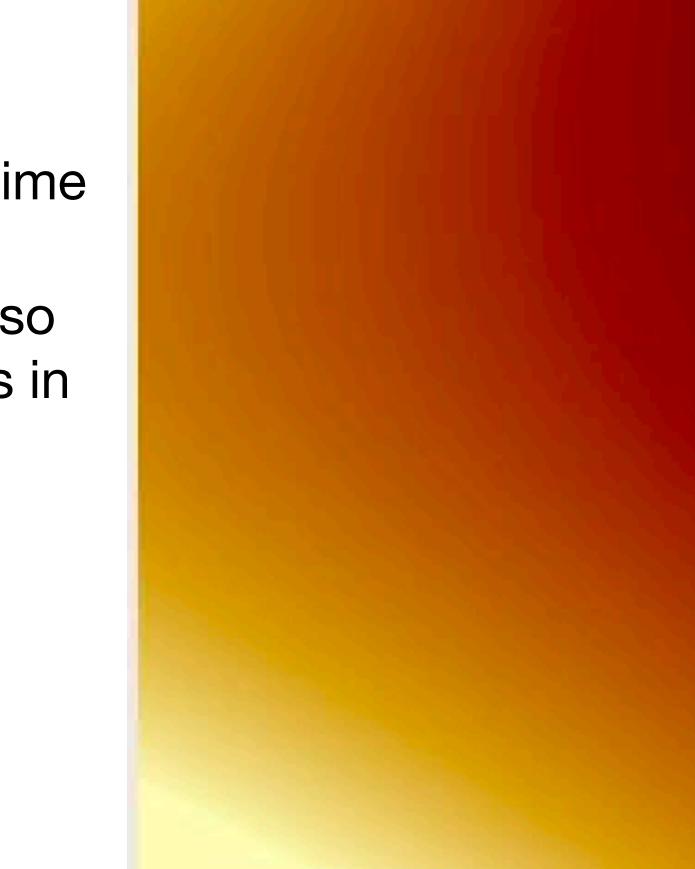




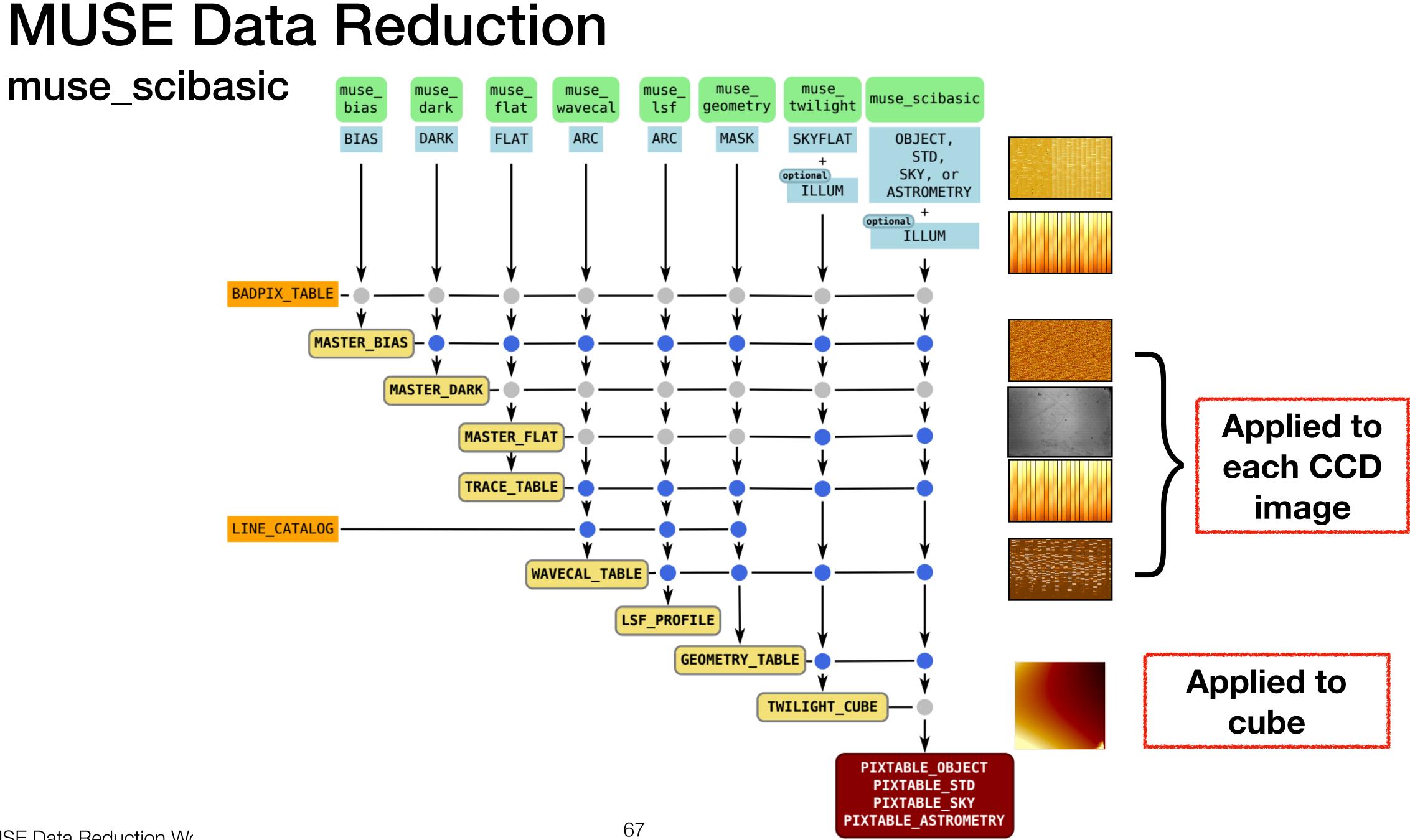
65

MUSE Data Reduction muse_twilight

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



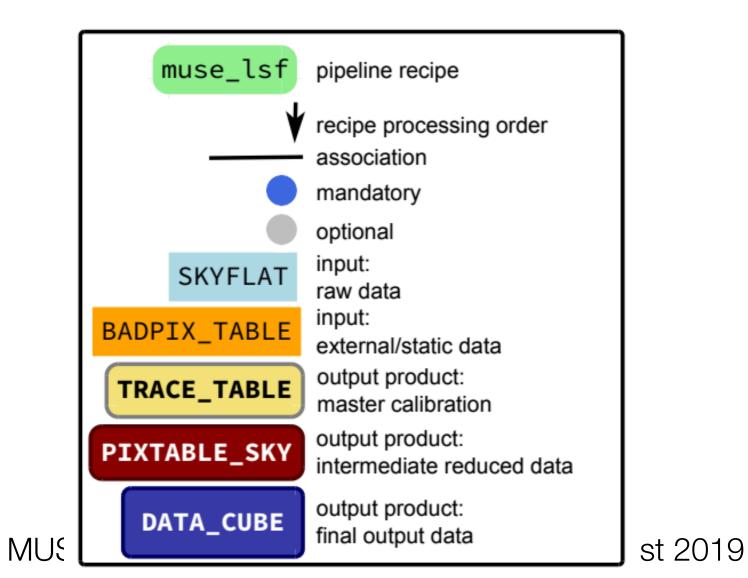


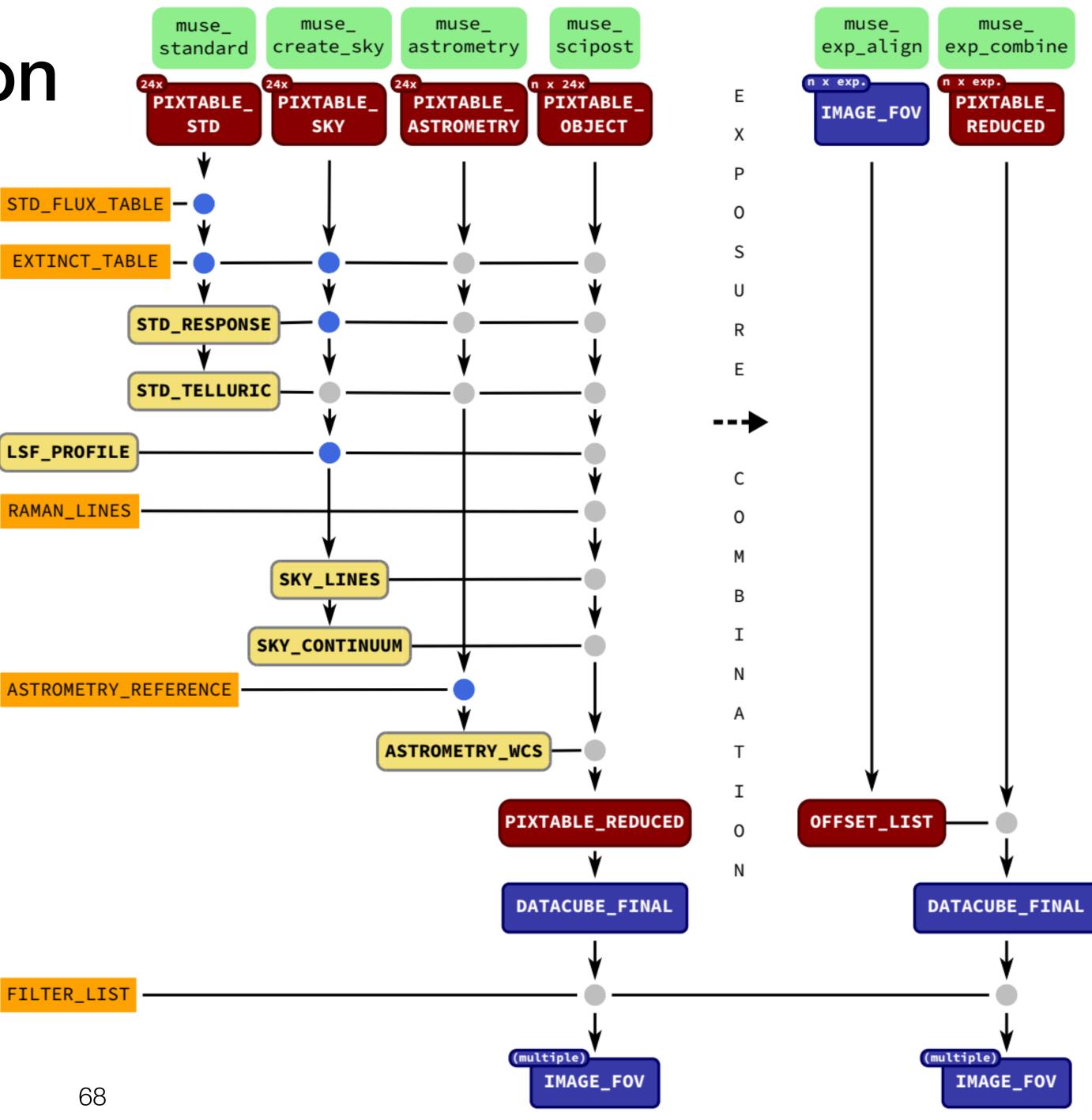


MUSE Data Reduction Wo

MUSE Data Reduction Post-processing

- Post-processing steps
 - muse_standard
 - muse_create_sky ${\color{black}\bullet}$
 - muse_astrometry
 - muse_scipost
 - muse_align
 - muse_combine



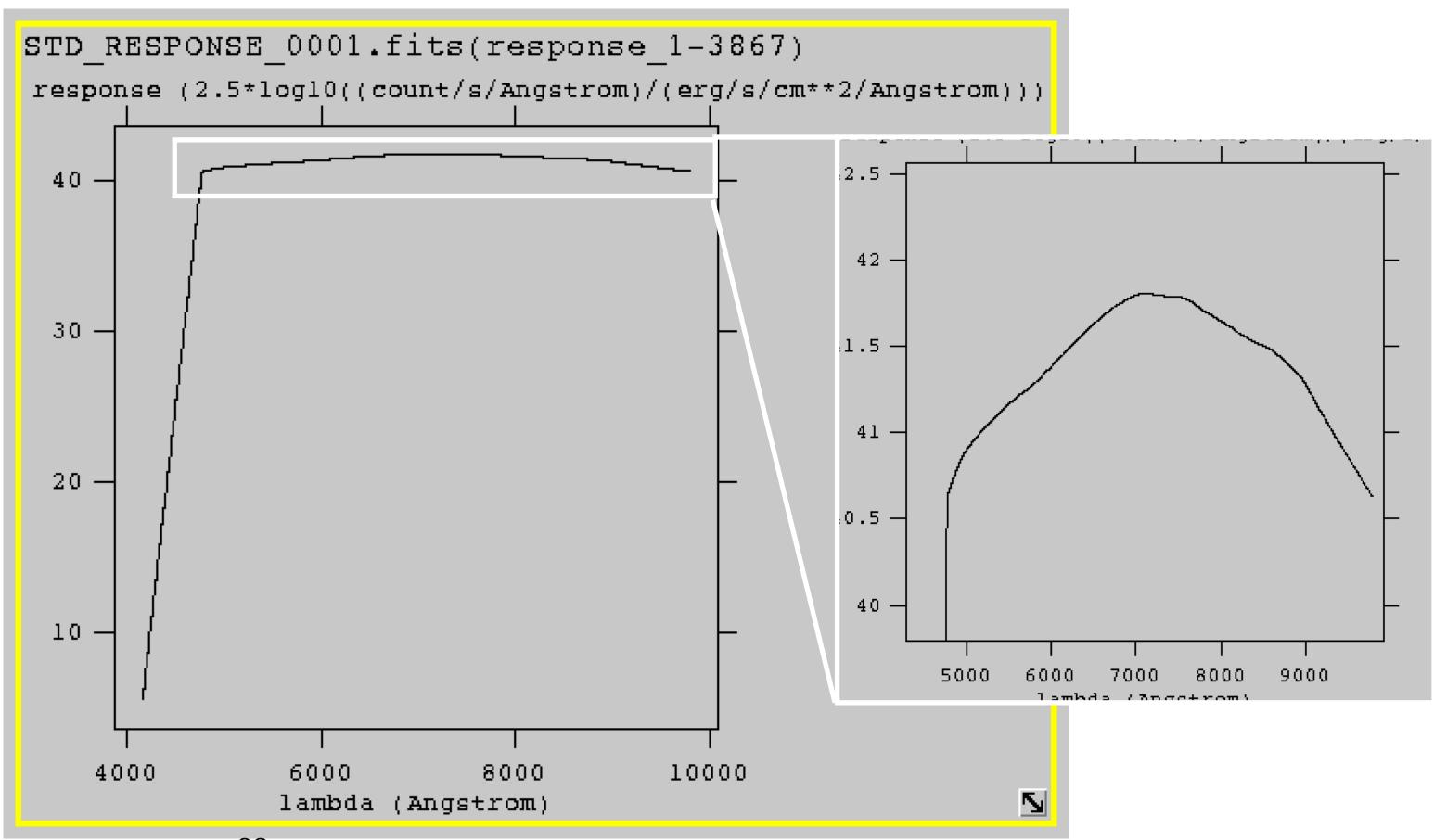


MUSE Data Reduction muse_standard

Measures the light from lacksquarea 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 \bullet is taken each night under clear conditions, and is only applicable to that nights observations



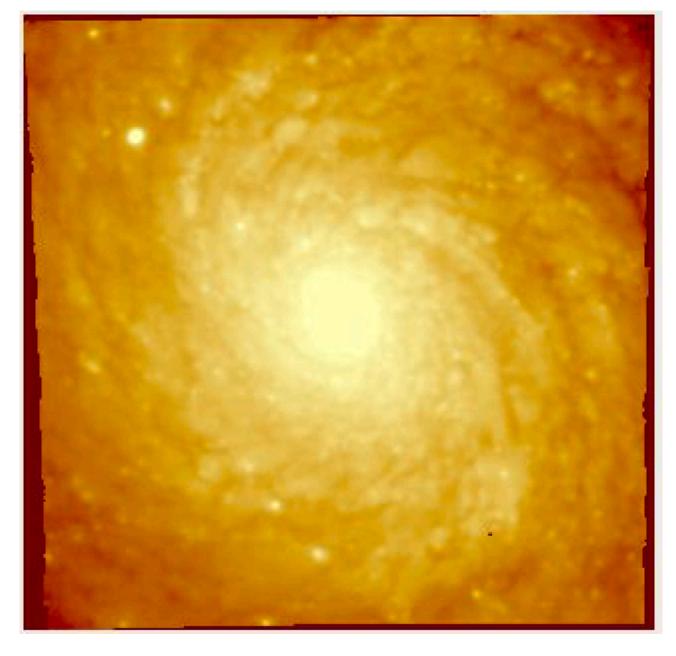
69

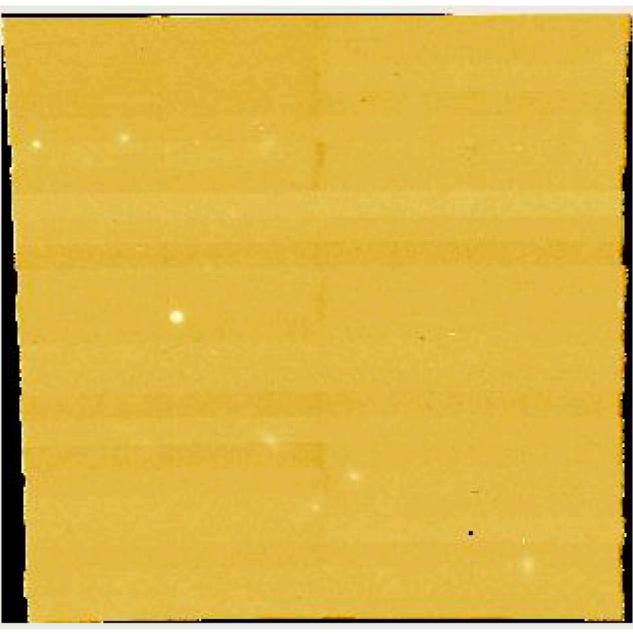
MUSE Data Reduction muse_create_sky

- exposure
- \bullet datacube

Target

Sky image



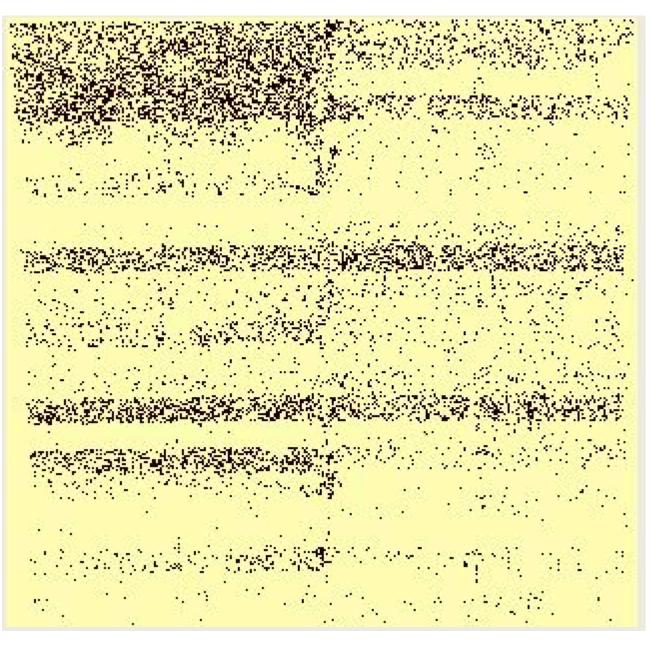


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Used **only** when the target covers most of the FOV and there is a dedicated sky

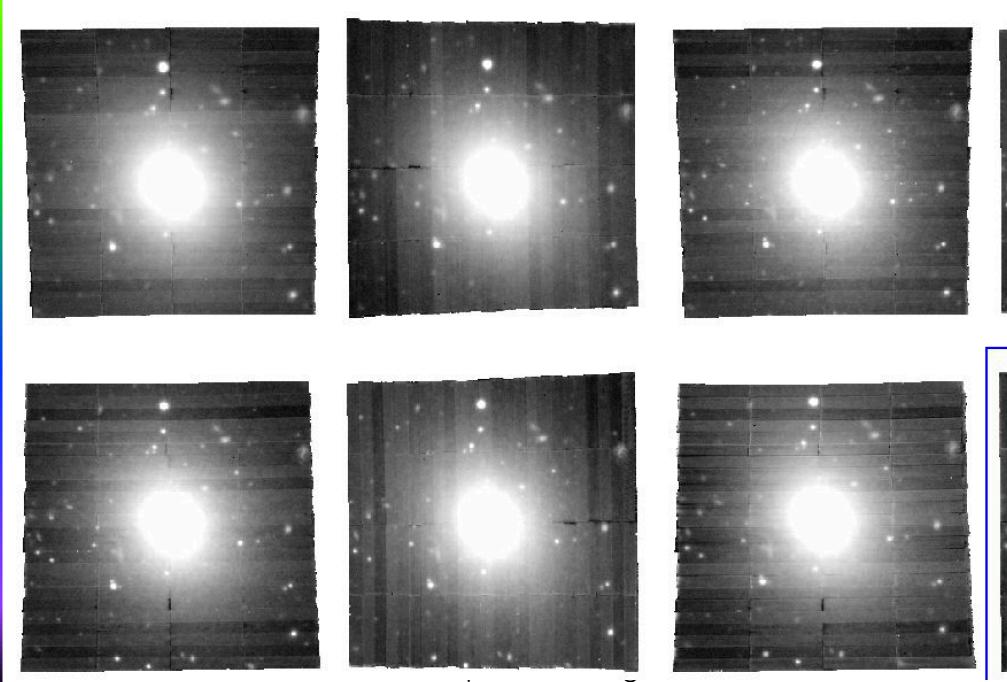
Creates the sky_mask and measures the sky continuum and emission lines across the

Sky mask

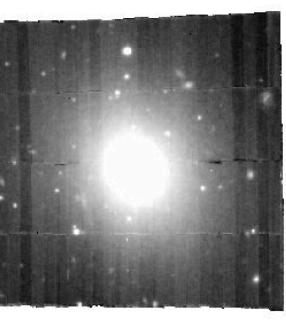


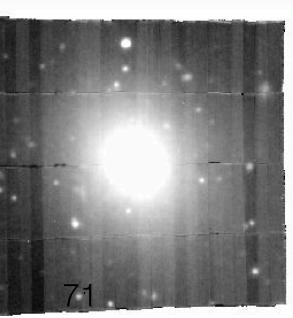
MUSE Data Reduction muse_scipost

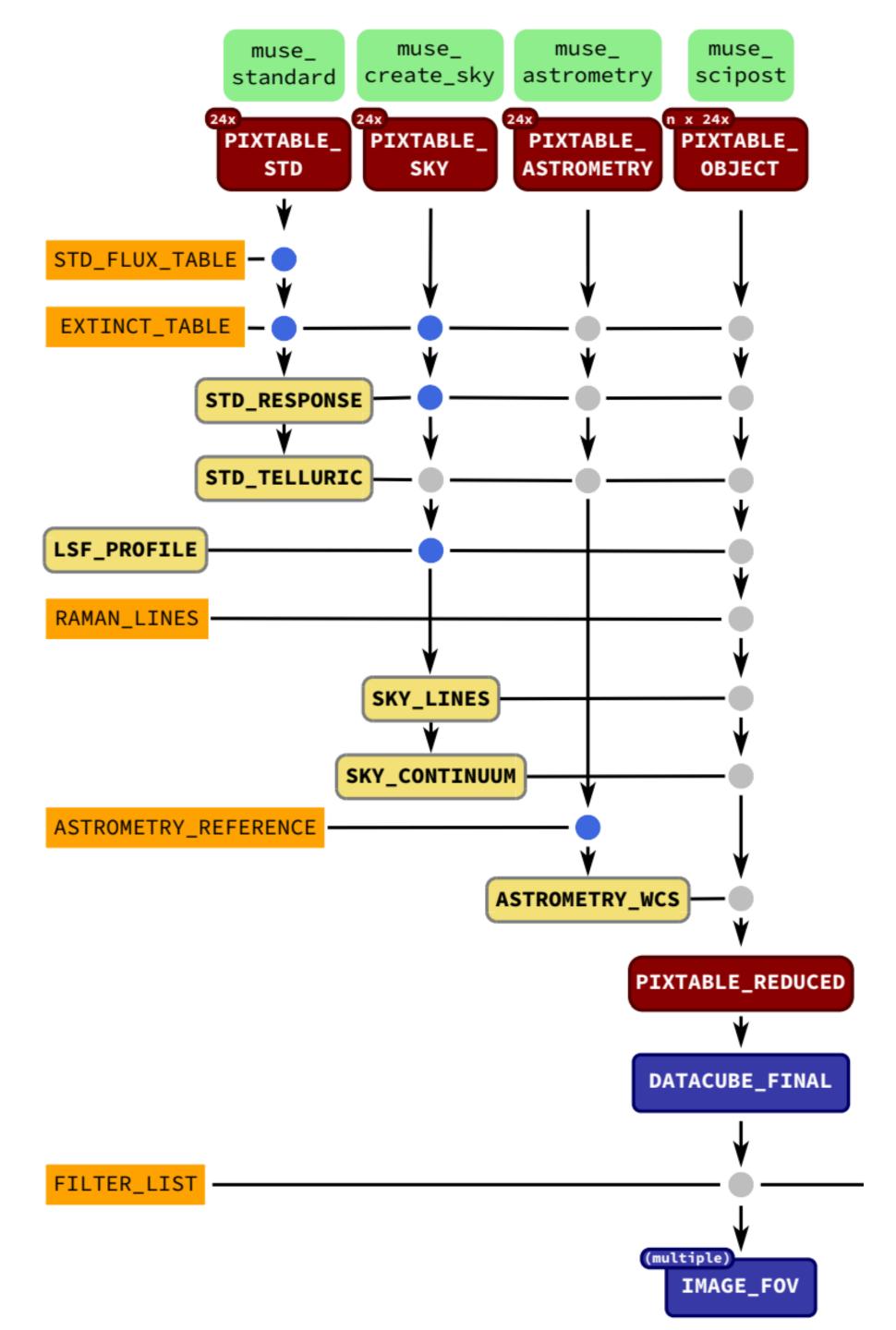
- Applies flux calibration, sky subtraction, and \bullet astrometry solution
- Converts pixel tables into data cubes for each \bullet exposure
- **One exposure at a time** \bullet





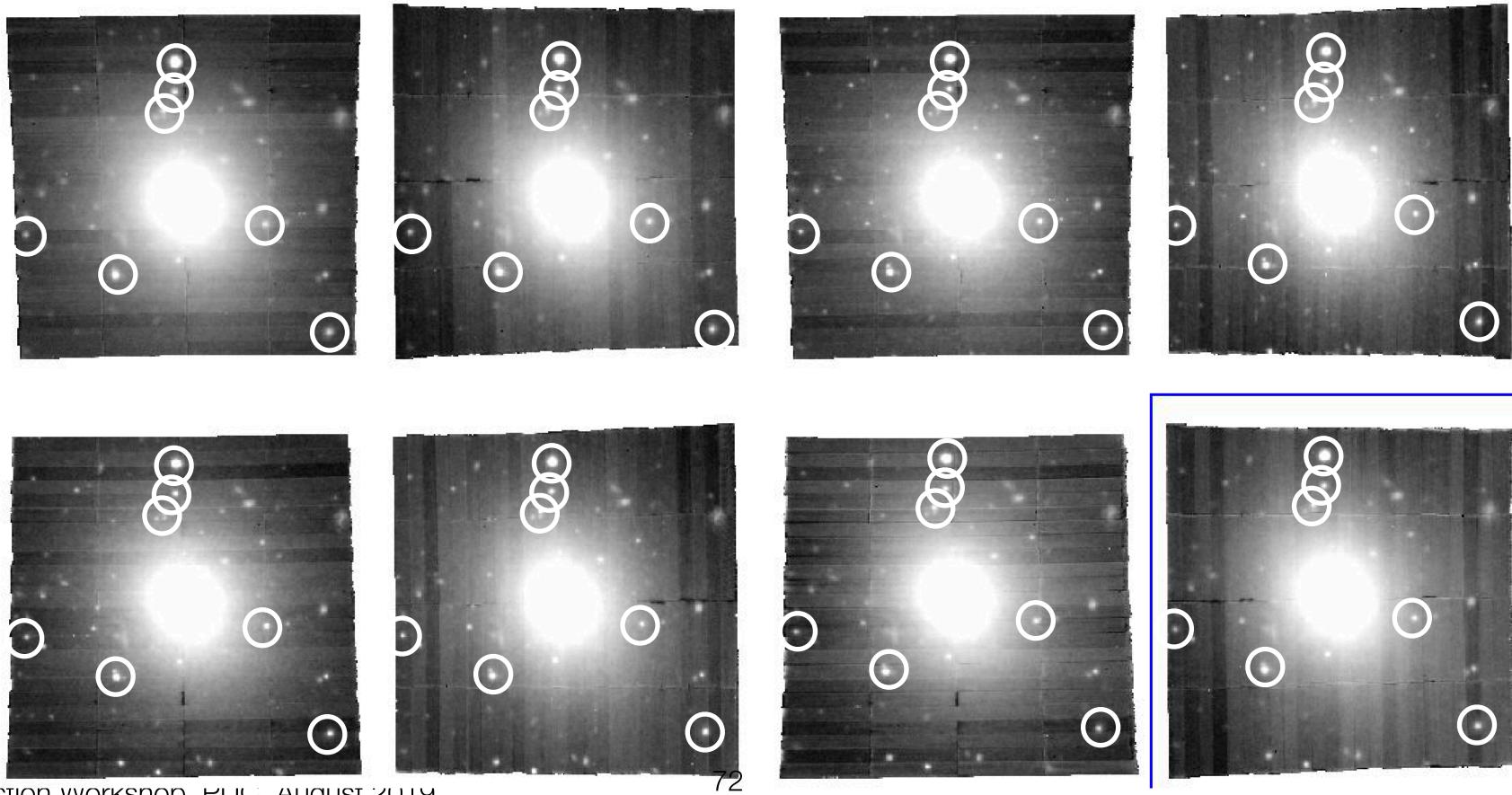


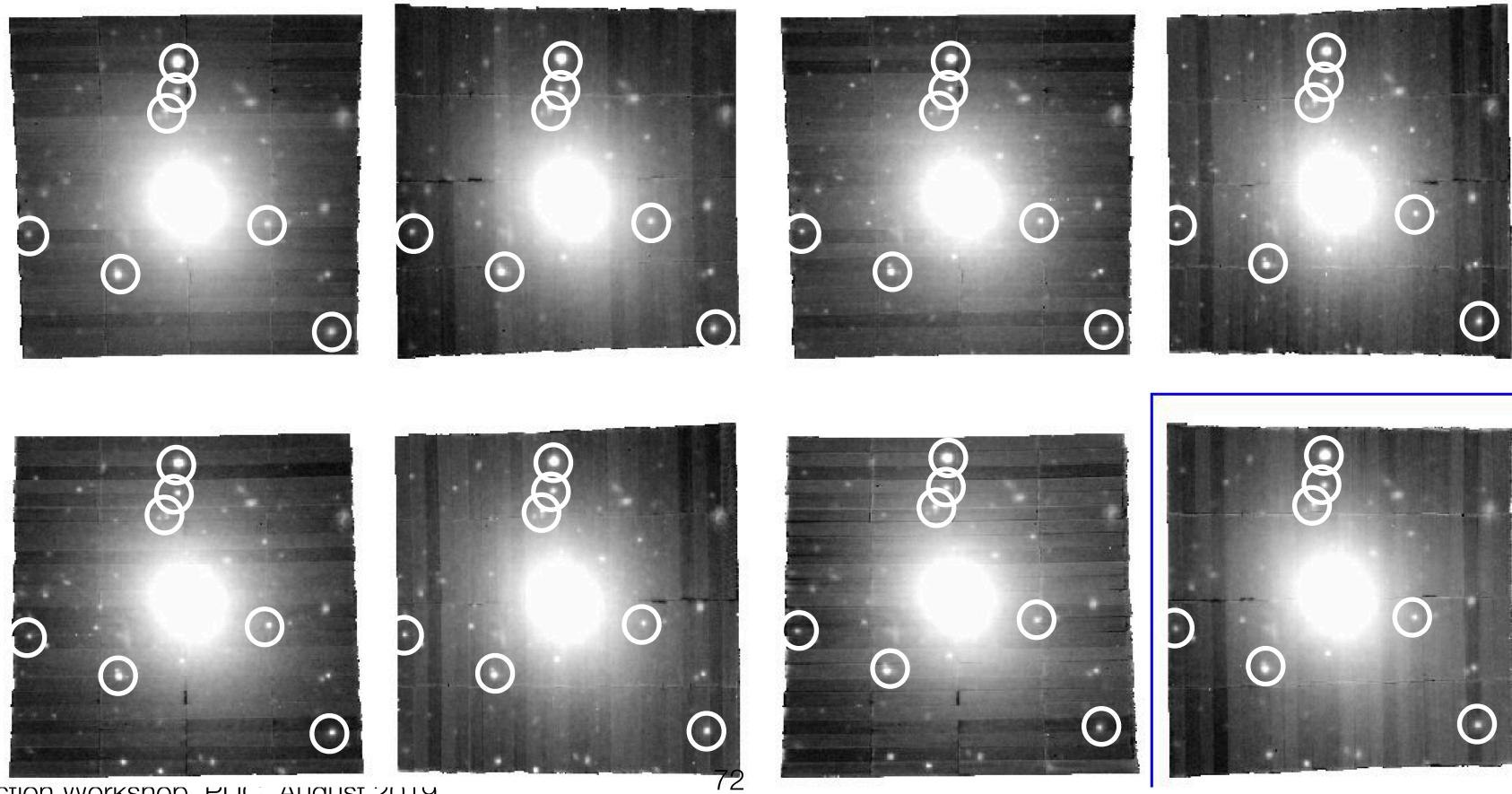




MUSE Data Reduction muse_align

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

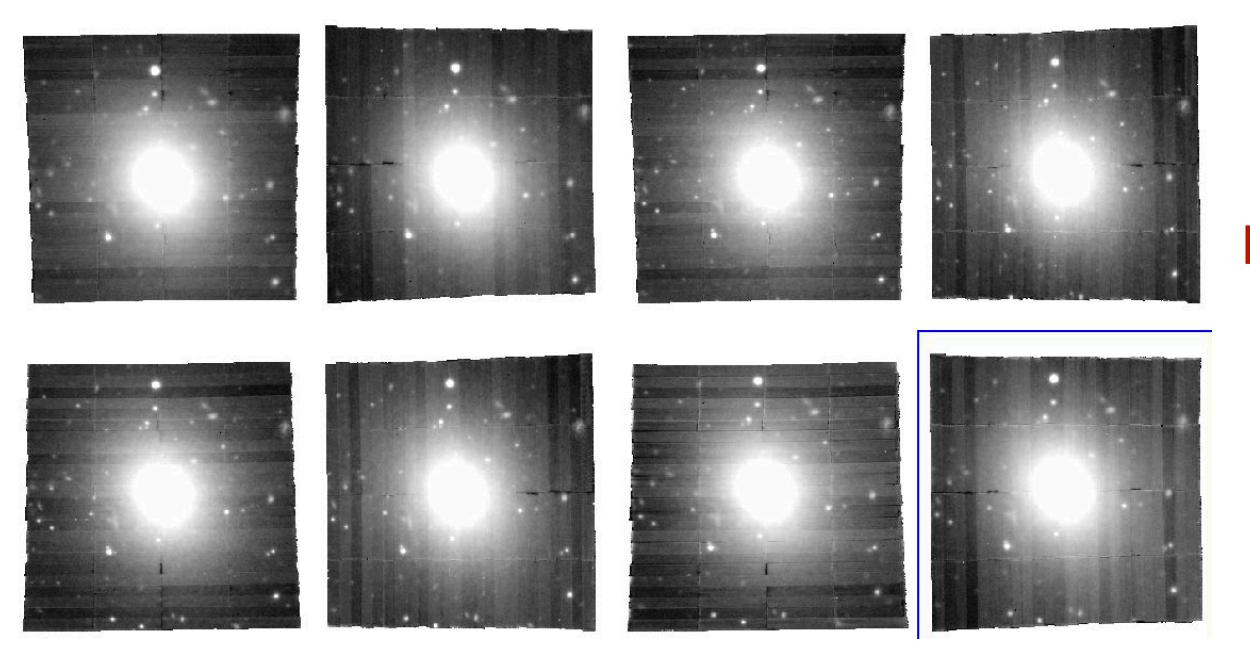




MUSE Data Reduction vvorksnop, PUC, August 2019

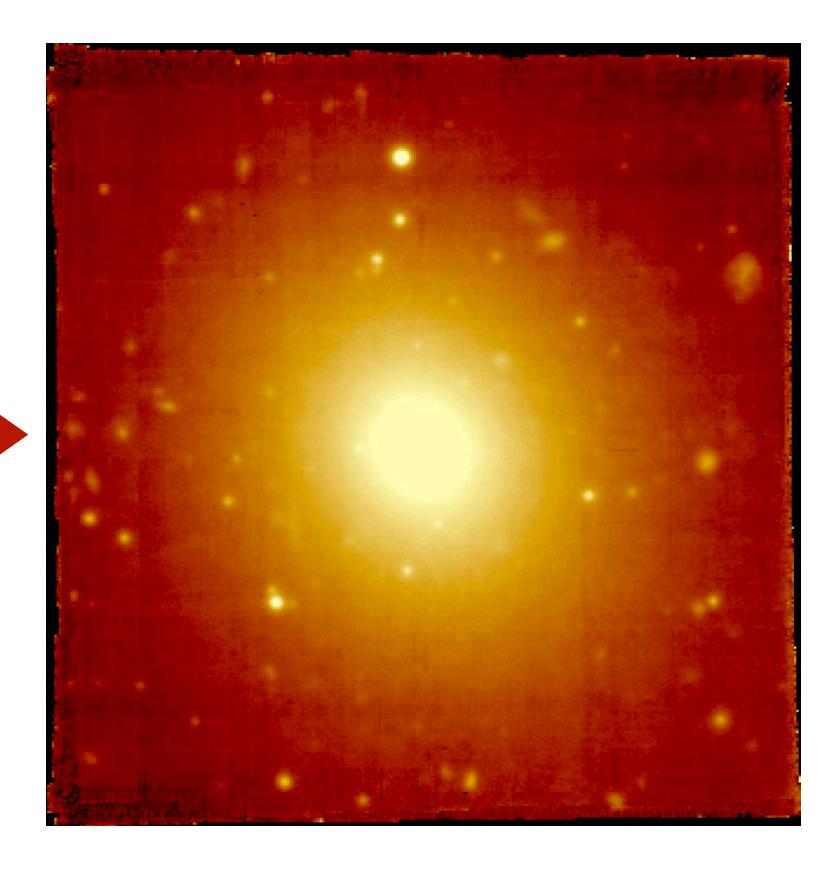
MUSE Data Reduction muse_combine

- Uses the offsets from muse_exp_align to stack the exposures
- \bullet very little overlap between exposures



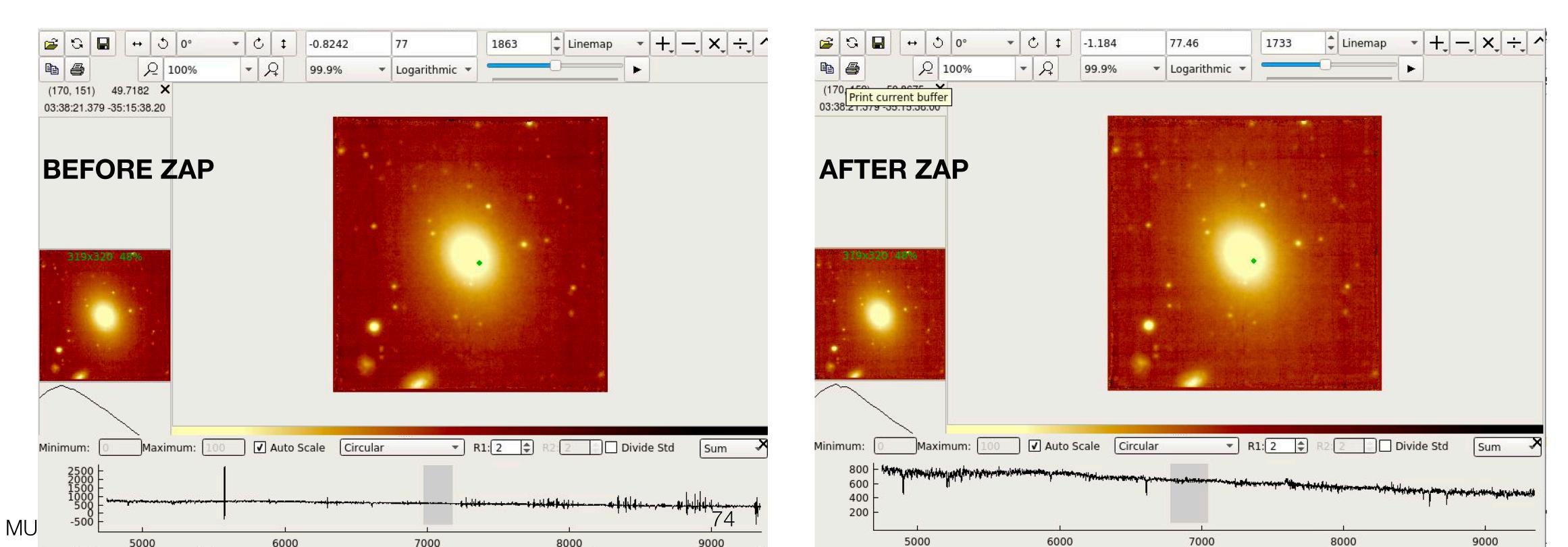
MUSE Data Reduction Workshop, PUC, August 2019

You can alternatively use the was information, especially when creating a mosaic with



MUSE Data Reduction ZAP: Zurich Atmospheric Purge code

- when applies to the final datacube
- Python code- parallelised to use every core available on the machine \bullet



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%

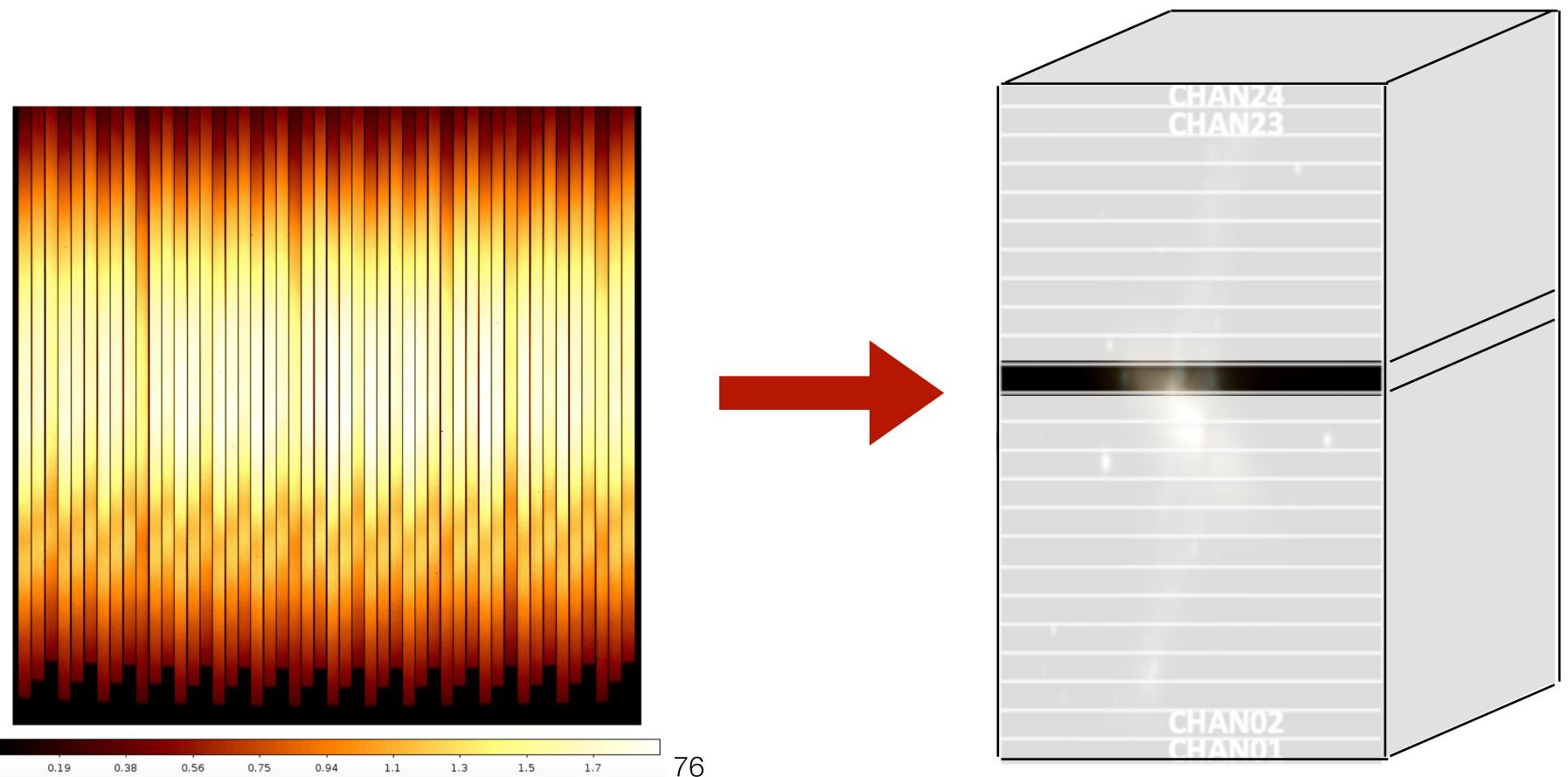
Please use the *nice* command when running on a shared machine (e.g. nice python)

MUSE Data Reduction Static calibrations

- **Bad Pixel Mask:** lists the bad pixels for each CCD \bullet
- **Extinction Table:** a measure of atmospheric extinction at Paranal as a function of wavelength
- **Filter List:** list of filter transmission curves \bullet
- 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 each CCD lies

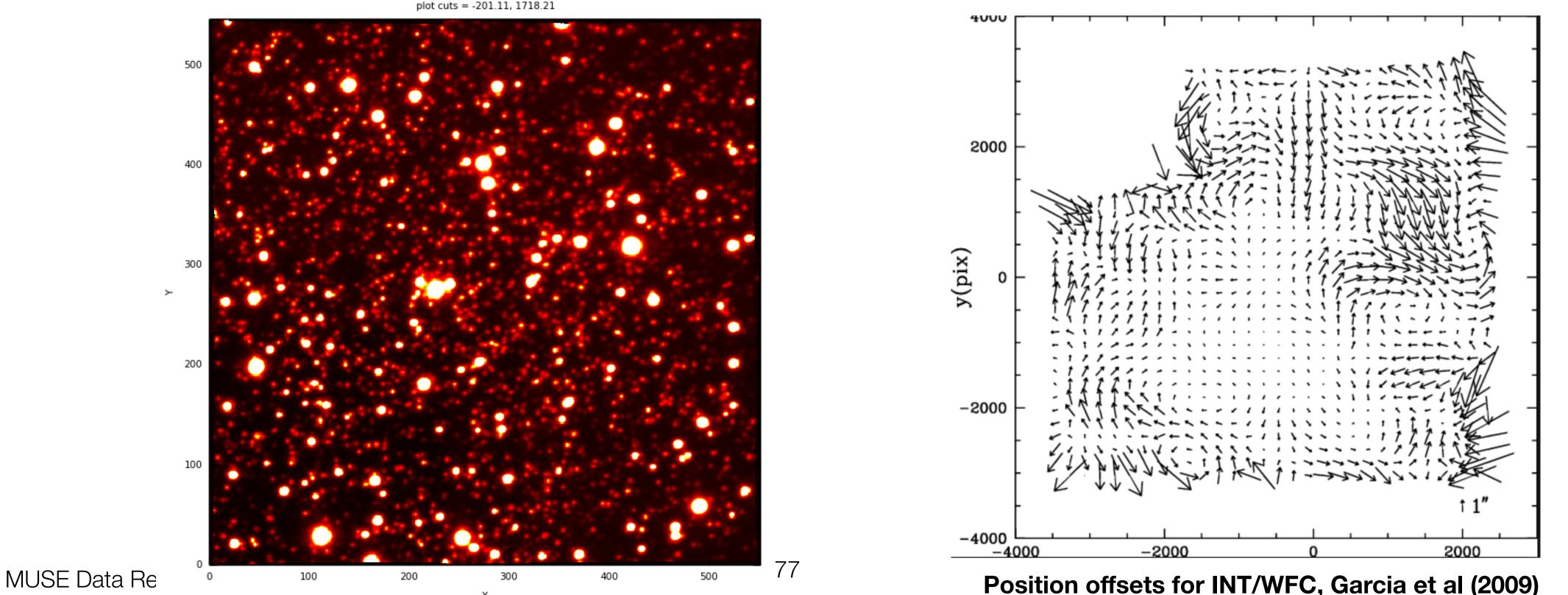


MUSE Data Reduction vvoirshop, 100, August 2013

Geometry Table: uses the trace table to identify where in the datacube each pixel in

MUSE Data Reduction Static calibrations

Also measures the PSF across the field



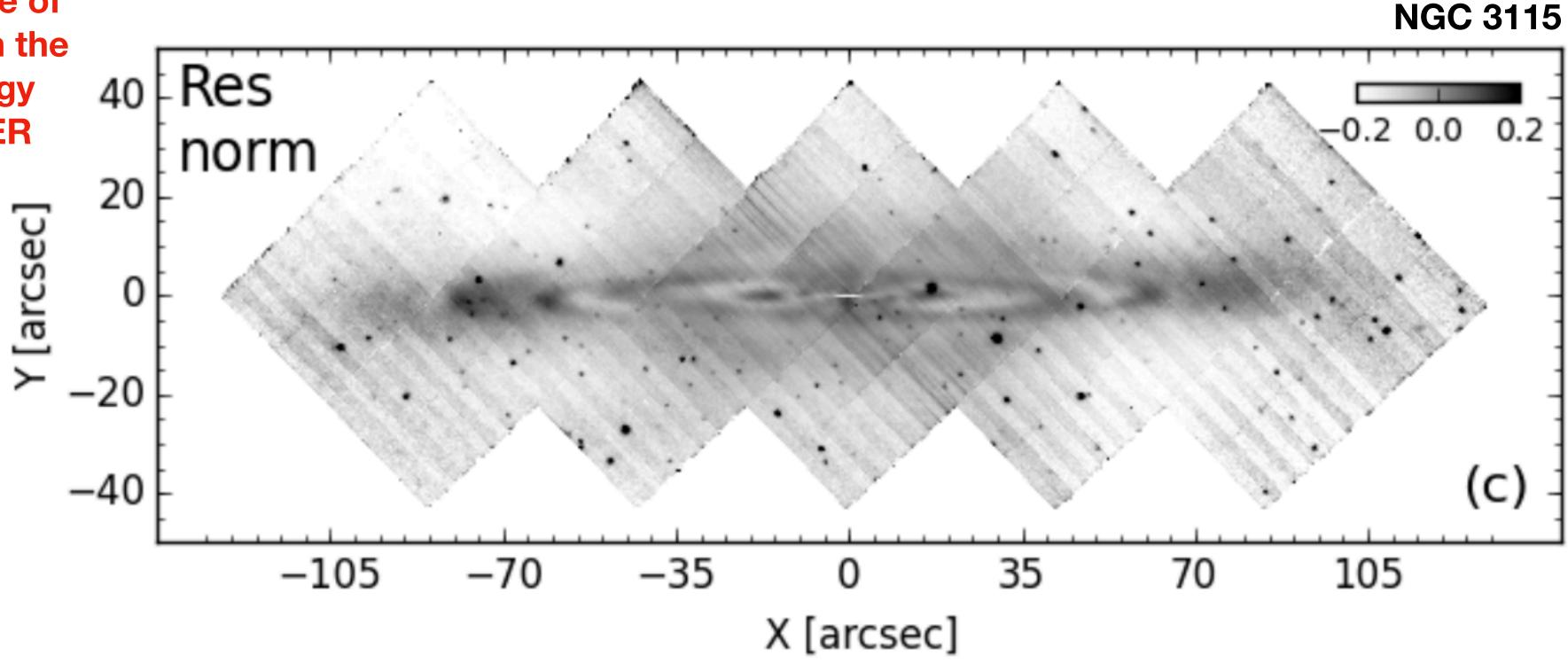
Astrometry WCS: takes an exposure of a star cluster, identifies point sources, and compares the locations with coordinates of known stars to measure offsets across FOV.

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

Troubleshooting Common issues when reducing MUSE data

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No offsets or rotations between <u>exposures</u> 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.



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Guereou et al (2016)



No illumination calibration The background level in each detector is temperature dependent 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.

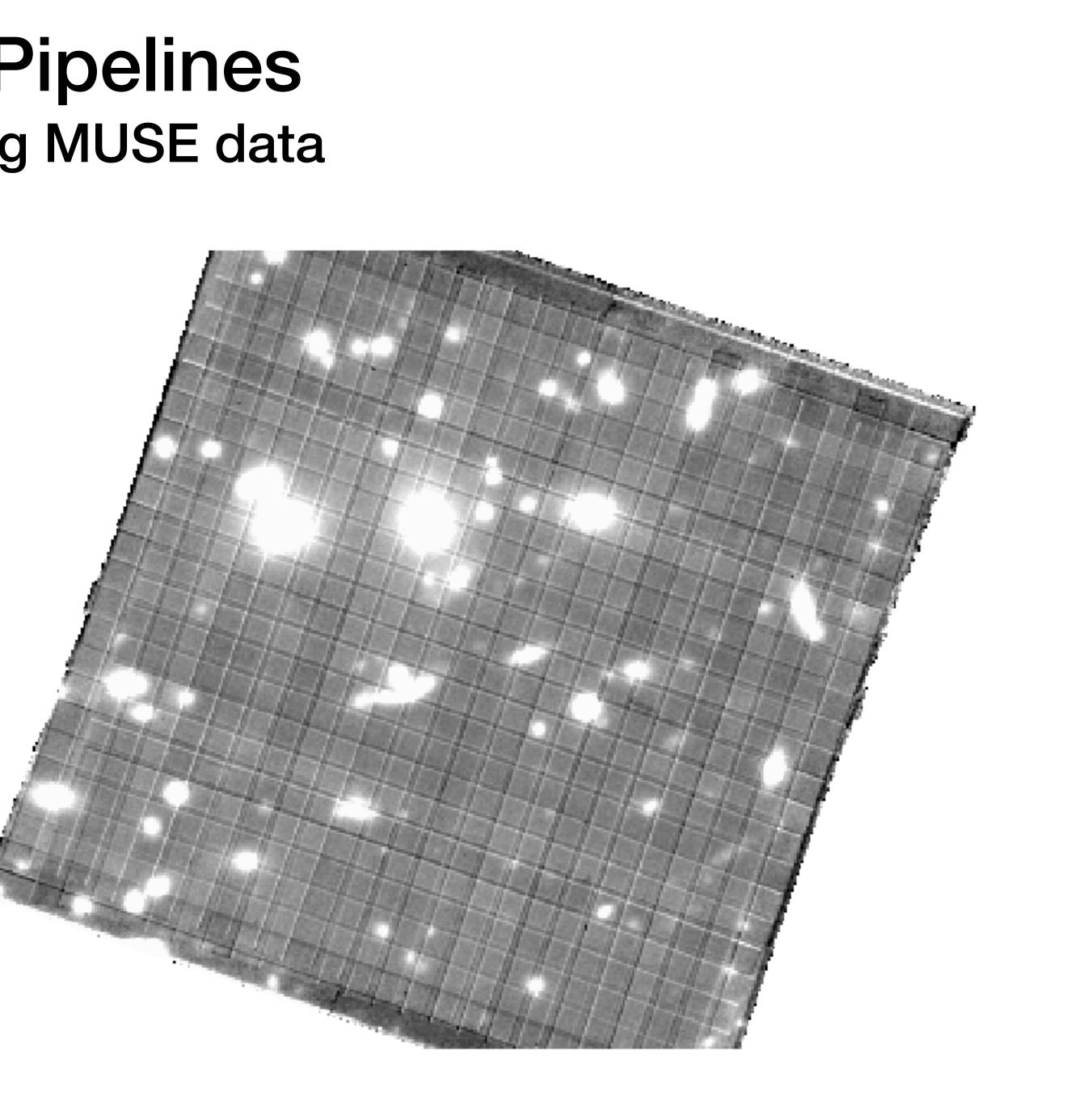
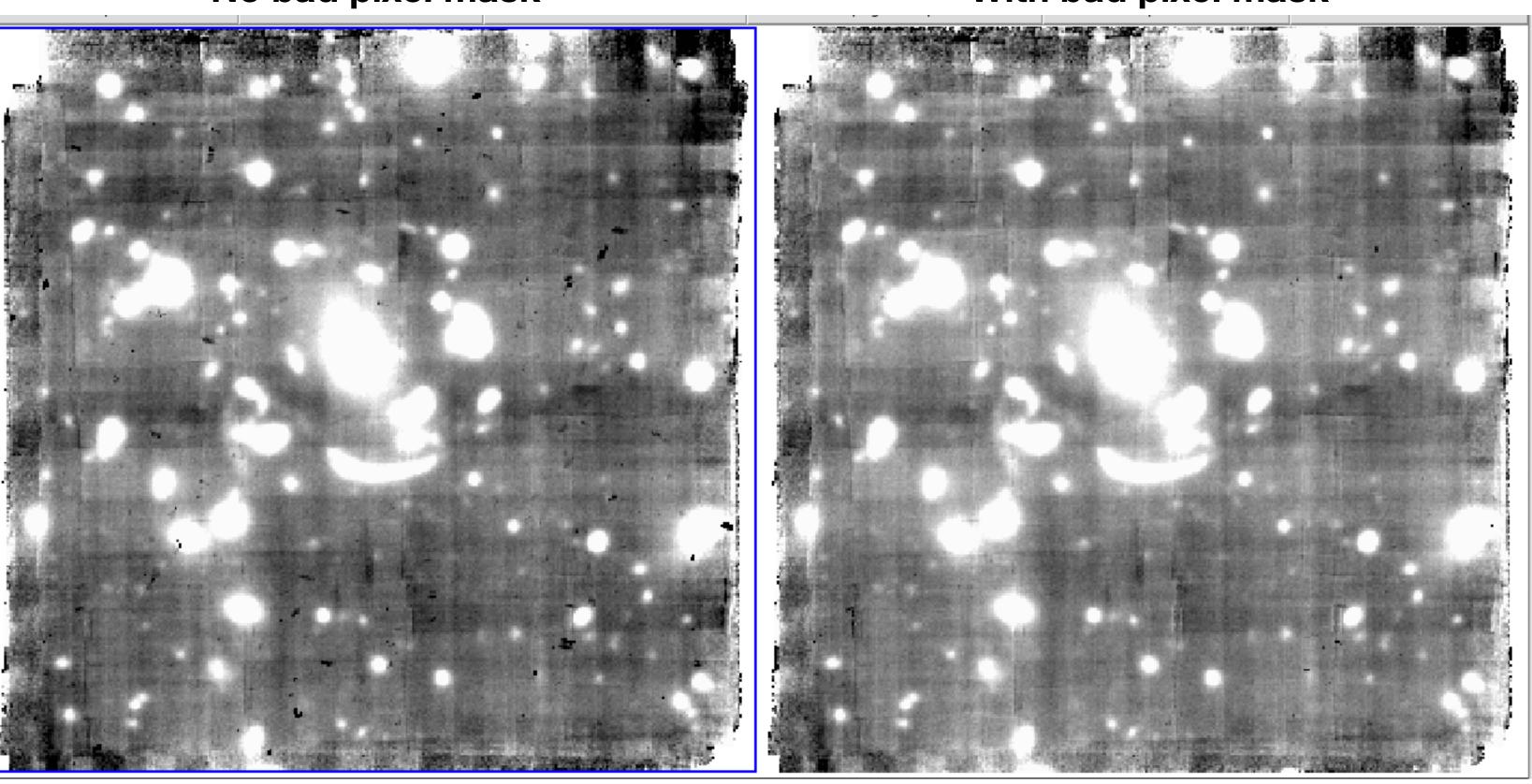


Image credit: Felipe Barrientos

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



MUSE Data Reduction Workshop, PUC, August 2019

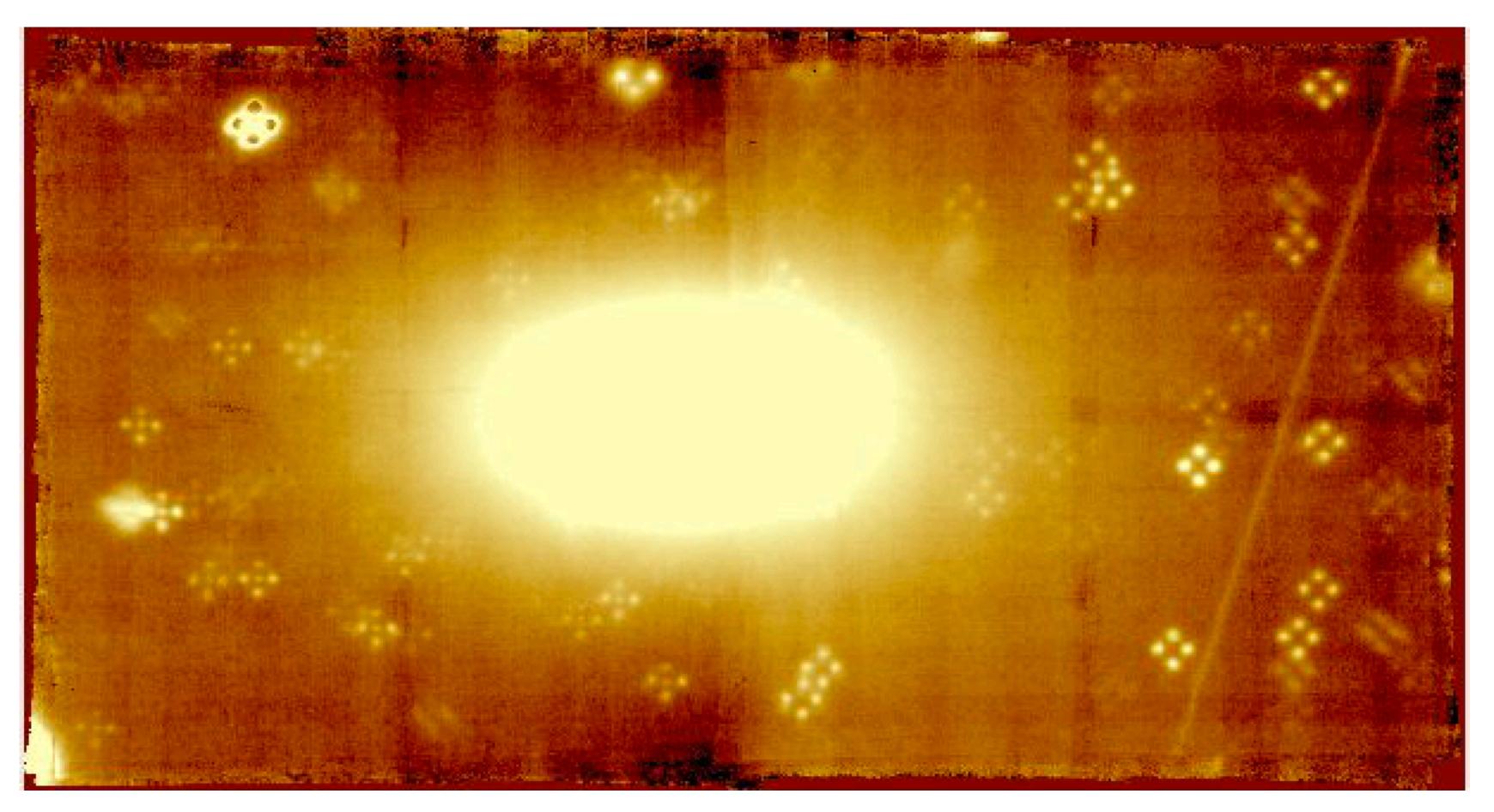
No bad pixel mask

With bad pixel mask

Image credit: Felipe Barrientos

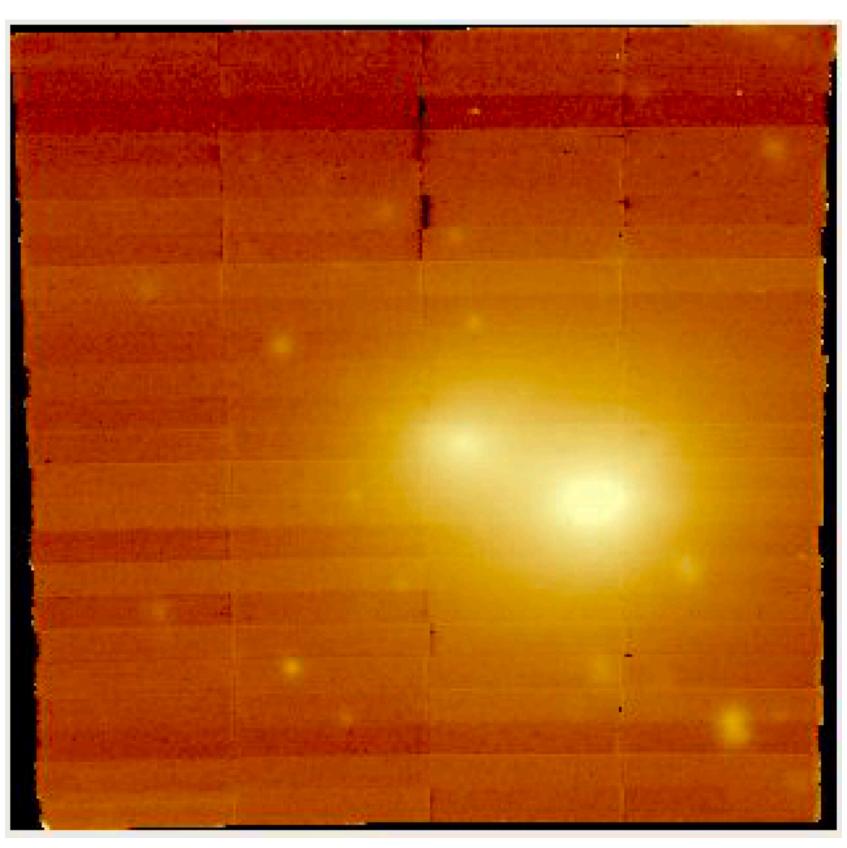
Offset list issues If there is very little overlap in the esposures, muse_exp_align can have issues finding enough stars to match for the alignment.

Note: In this example I also omitted the first channel in the scipost step, offsetting the WCS by ~2".



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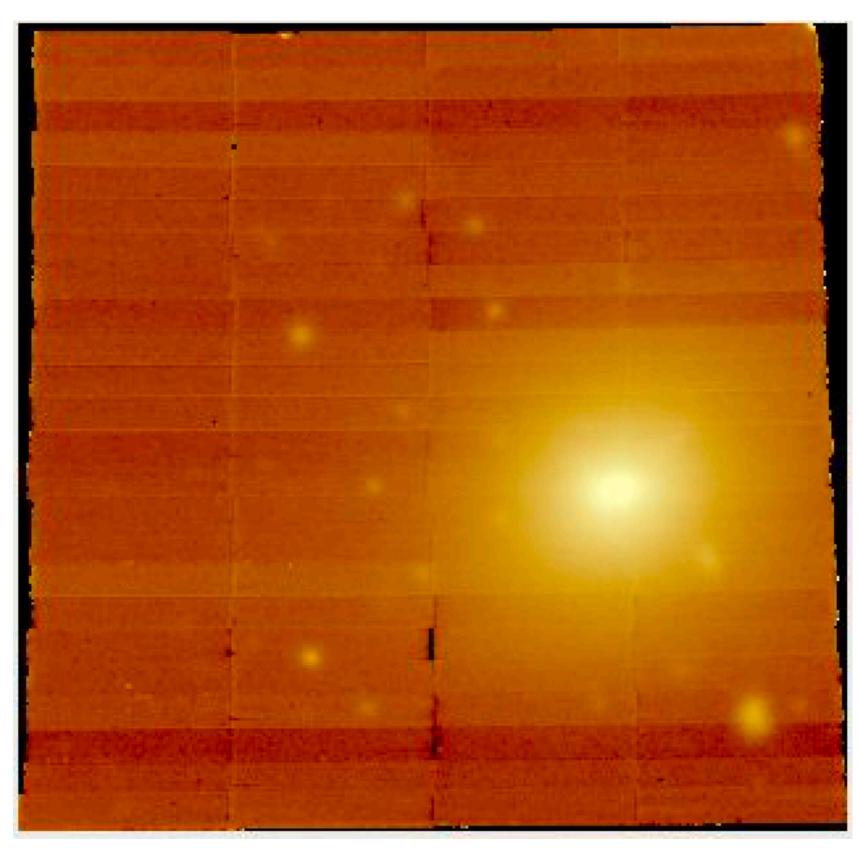
Telescope jumps Occasionally, the telescope might jump or lose the tracking. This most often happens when there are thick clouds that obscure the guide star.



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Telescope jumps

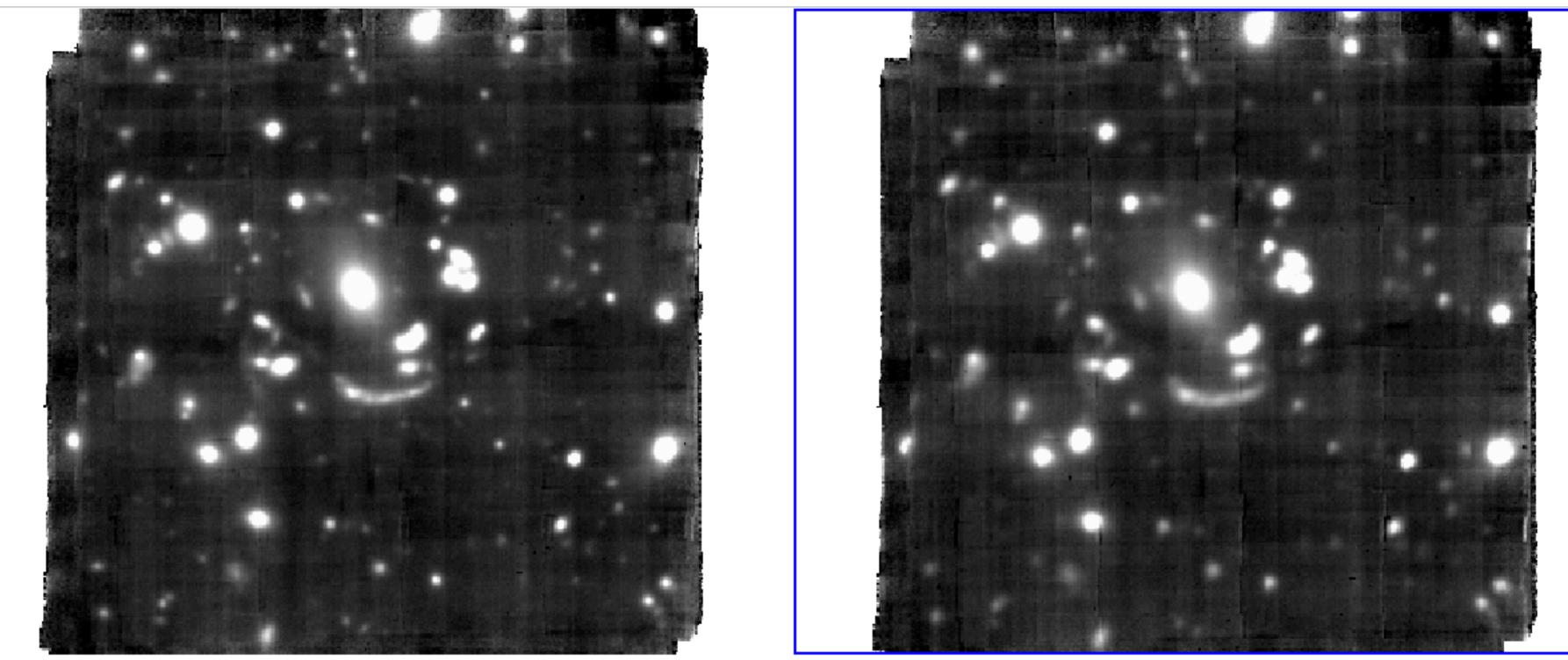
Telescope maintains the guiding





No offset list provided pipeline stacks images using simply the WCS information

With offset list



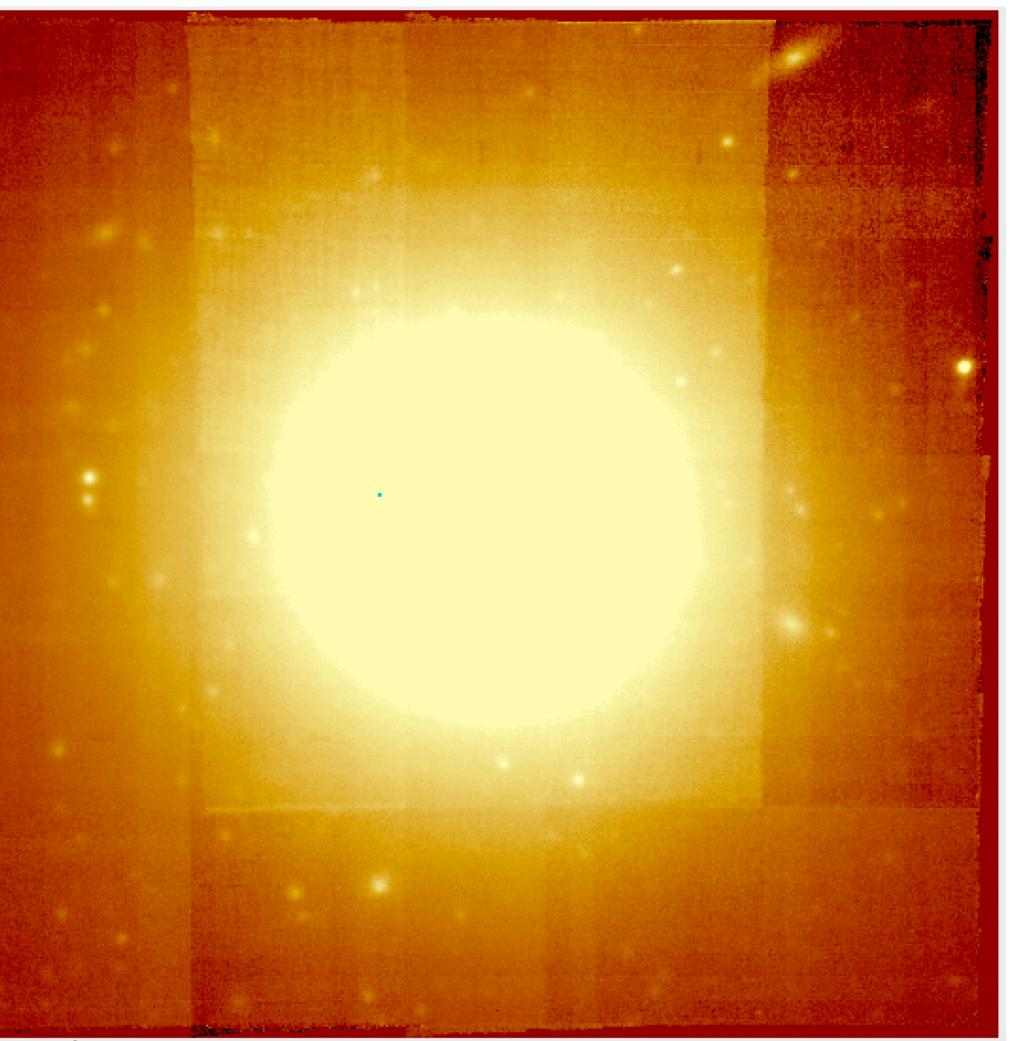
MUSE Data Reduction Workshop, PUC, August 2019

No offset list

Image credit: Felipe Barrientos



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?

MUSE Data Reduction Workshop, PUC, August 2019



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**

- 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.

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

How to Visualize MUSE data?

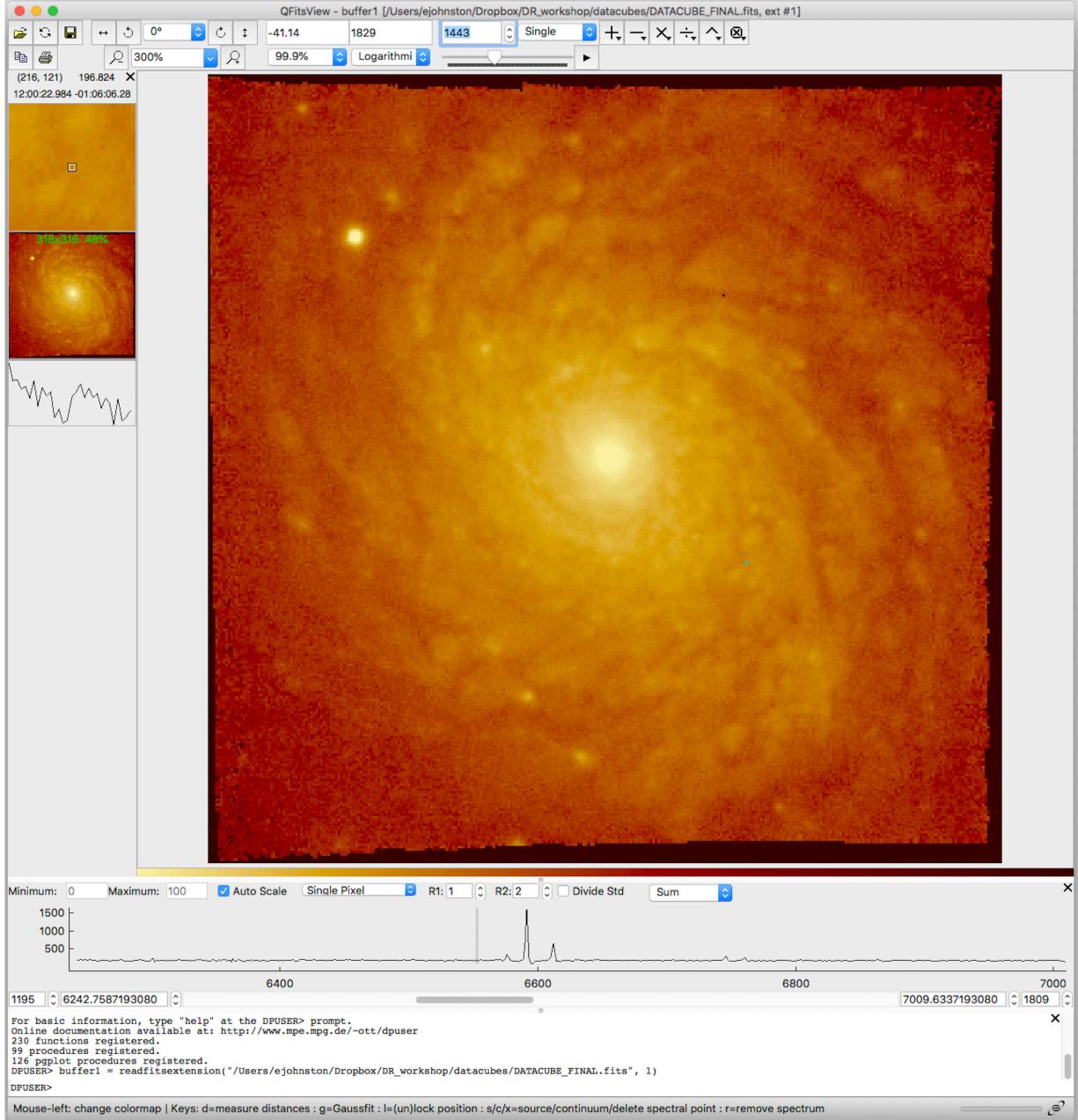
- DS9
- QFITSview
- Pingsoft
- MuseCube

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How to Visualize MUSE data?

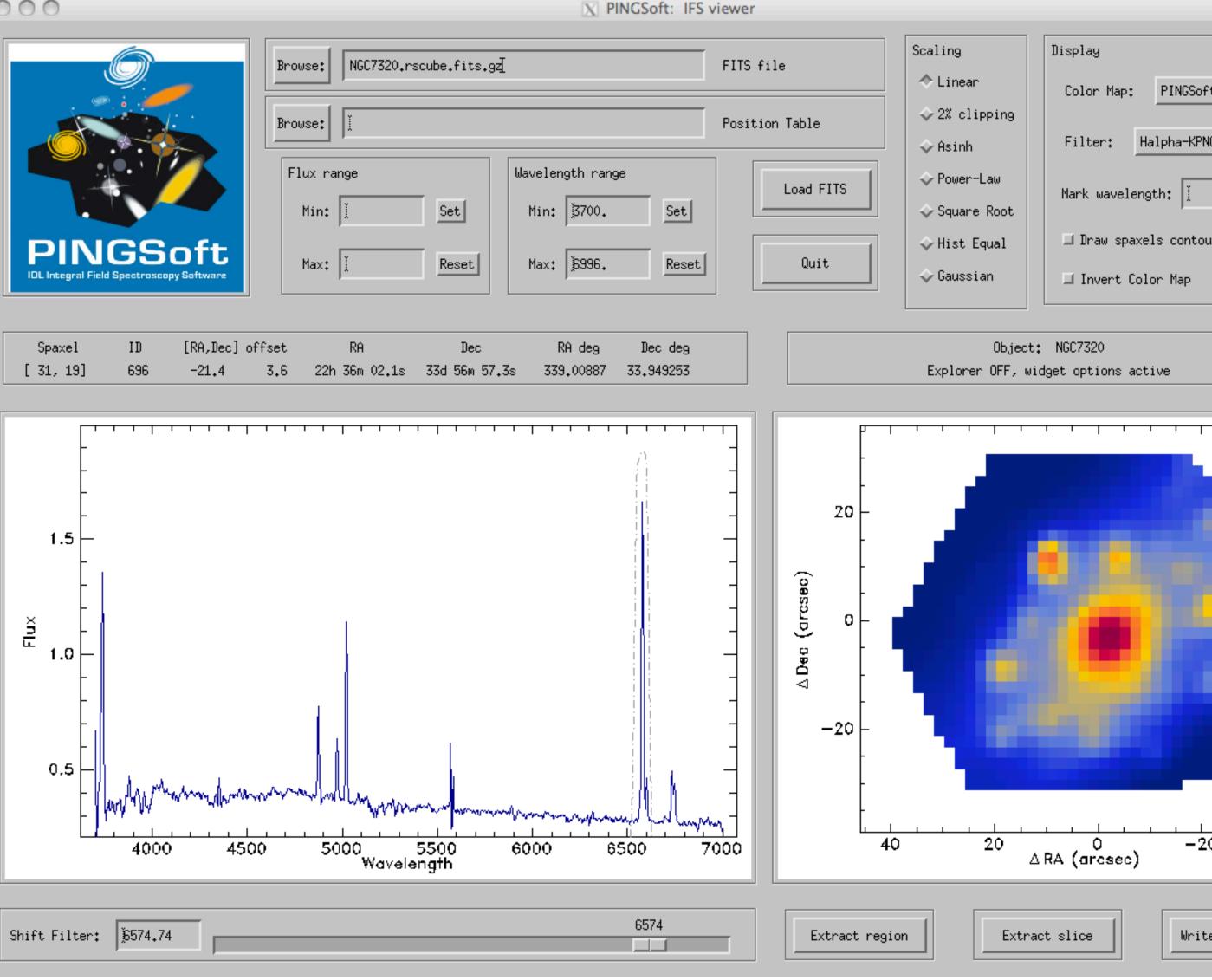
- DS9
- QFITSview
- Pingsoft
- MuseCube

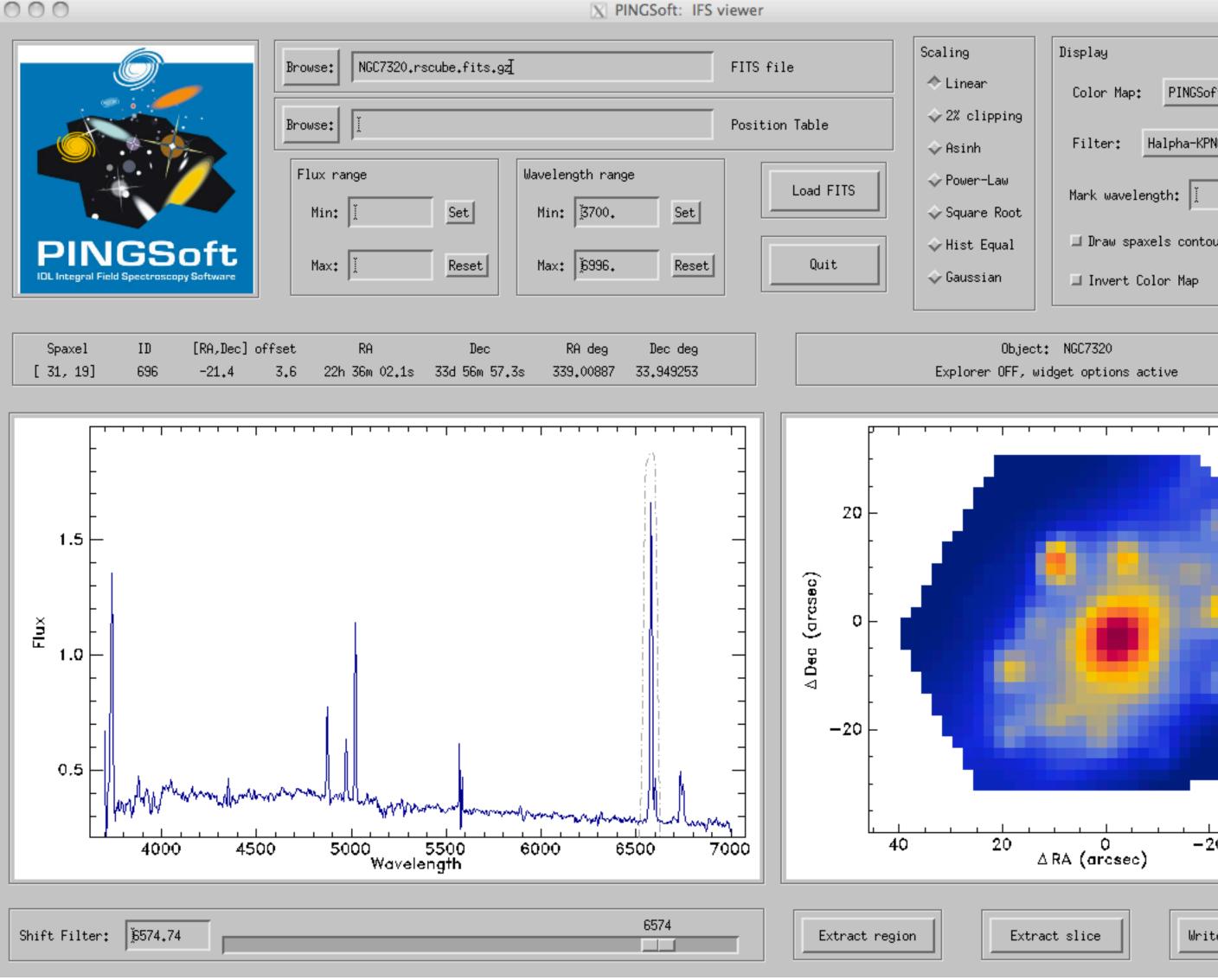


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How to Access MUSE data? How to Visualize MUSE data?

- DS9
- QFITSview
- Pingsoft
- MuseCube





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X PINGSoft: IFS viewer

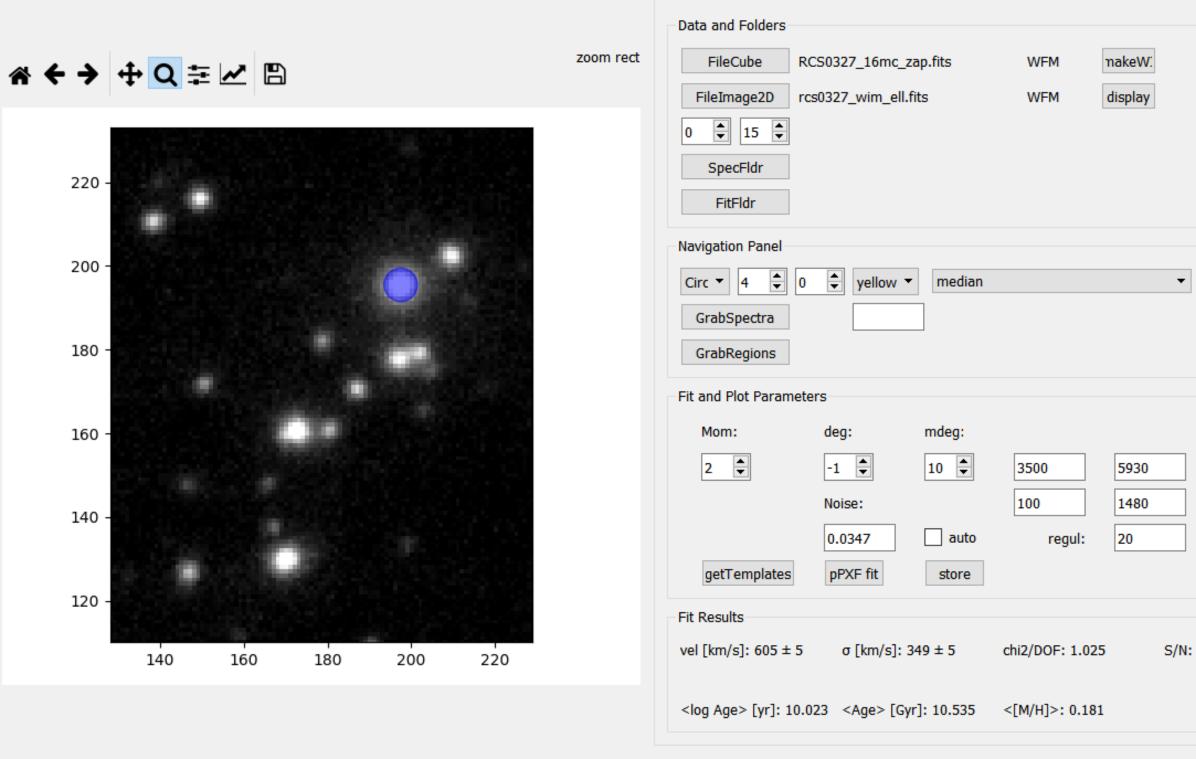
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How to Access MUSE data? How to Visualize MUSE data?

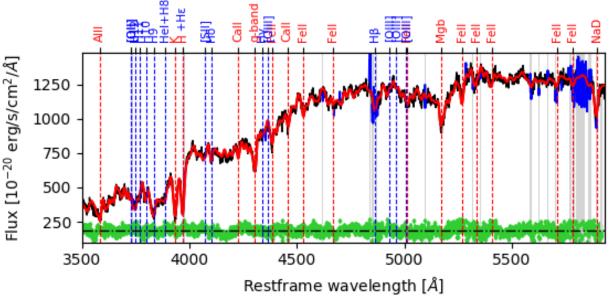
- DS9
- QFITSview
- Pingsoft
- MuseCube

MuseCube Gui (G. D'Ago, IA-PUC)

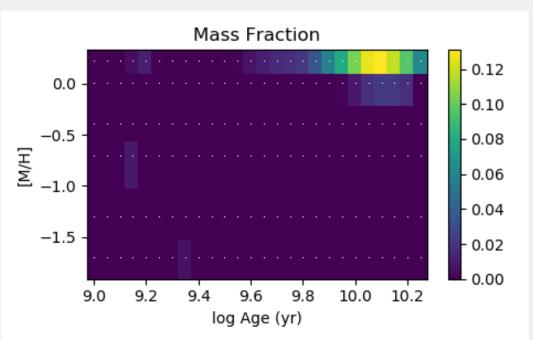


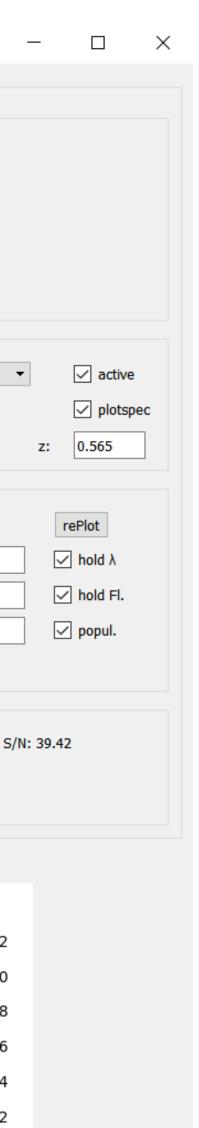
Tool Box

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Useful Links

- MUSE homepage \bullet
- MUSE User Manual: \bullet 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

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https://www.eso.org/sci/facilities/paranal/instruments/muse/overview.html

Useful Links

 \bullet can experiment with are available on my webpage:

https://evelynj.github.io/MUSE_DR_workshop.html

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These slides, the exercises for the workshops and some example datacubes that you

MUSE DR workshops

7th August

- Julio Olivares
- Daniela Soto
- Nicholas M
- Felipe Barrientos
- Chelsea Spengler
- Thomas Puzia
- Yu Rong
- Sebastian Lopez

<u>9th August</u>

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

Giordano Bruno, 14:00

Please remember to download the X2go software and bring your laptop

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23rd August

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