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Leibniz-Institut für
Astrophysik Potsdam

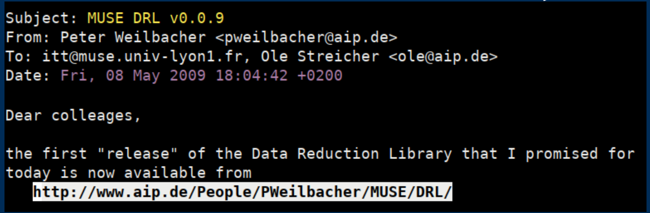
Nuisance or revolution?
15 years of MUSE data reduction

multi unit spectroscopic explorer

Peter Weilbacher (AIP) / MUSE 10yr Conference / Nov. 2024

MUSE data reduction history

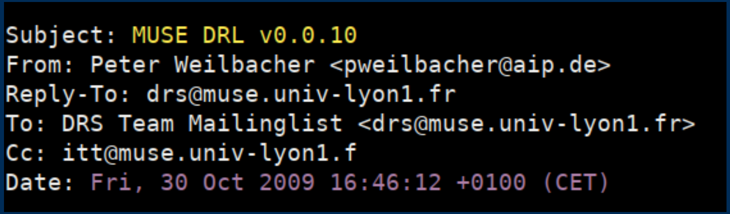
- involvement with MUSE since 2005
- 2024: 15 yr anniversary for me
  - 1st MUSE pipeline releases (consortium internal)
    "MUSE DRL v0.0.09" on 08 May 2009 and "MUSE DRL v0.0.10" on 30 Oct 2009



Subject: MUSE DRL v0.0.9
From: Peter Weilbacher <pweilbacher@aip.de>
To: itt@muse.univ-lyon1.fr, Ole Streicher <ole@aip.de>
Date: Fri, 08 May 2009 18:04:42 +0200

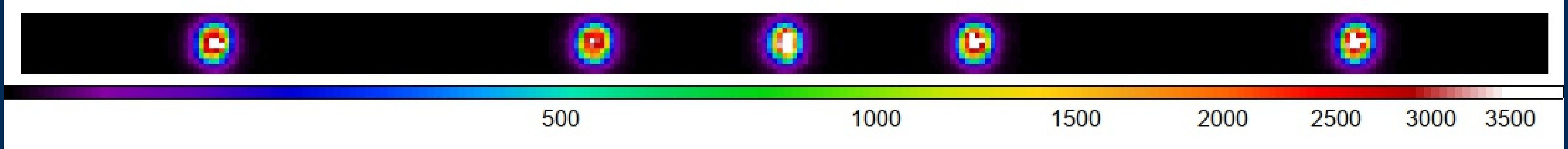
Dear colleagues,

the first "release" of the Data Reduction Library that I promised for
today is now available from
http://www.aip.de/People/PWeilbacher/MUSE/DRL/



Subject: MUSE DRL v0.0.10
From: Peter Weilbacher <pweilbacher@aip.de>
Reply-To: drs@muse.univ-lyon1.fr
To: DRS Team Mailinglist <drs@muse.univ-lyon1.fr>
Cc: itt@muse.univ-lyon1.f
Date: Fri, 30 Oct 2009 16:46:12 +0100 (CET)

  - 1st time to handle simulated MUSE science exposure (INM Stars, 4 Dec 2009)



  - Also 15 years for Ole Streicher as pipeline co-developer at AIP

Integral Field Spectrographs and Data Reduction

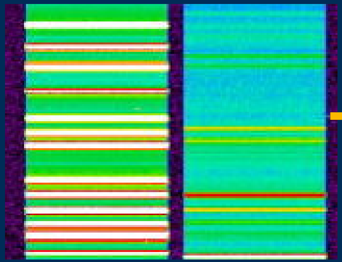
- IFUs with fibers / lenslets / slices have different issues with calibration
- Very complex data reduction problem, people used:
  - IRAF
  - some homegrown IDL scripts
  - p3d (`https://p3d.sourceforge.io/`)
  - an official instrument pipeline
  - a wild adaptation of an official pipeline
  - a secret pipeline
  - everything often involving cumbersome or tedious manual interaction

Integral Field Spectrographs and Data Reduction

- IFUs with fibers / lenslets / slices have different issues with calibration
- Very complex data reduction problem, many steps, some **involving resampling**:
  - remove CCD features
  - find data on the CCD (tracing)
  - **wavelength-calibrate**
  - **extract** (curvature)
  - position on sky
  - **correct for atmospheric refraction**
  - subtract sky
  - **correct for Earth motion (helio- / barycentric velocities)**
  - **(correct distortions)**
  - **apply exposure offsets**
  - combine exposures
- originally considered for MUSE as the ”baseline“ approach

MUSE Data Reduction

- the “enhanced” approach: **resample only once**!
- transform data from implicit to explicit coordinates ⟶ **pixel table**



create table

x	y	λ	value	flag	variance
-75.004	11.55	8408.7	87.72	0	19785.9
-75.003	11.55	8410.0	10.68	0	19655.3
-75.002	11.55	8411.2	43.55	0	20630.6
-75.000	11.55	8412.5	85.31	5	21929.7
-149.982	7.55	4212.9	1281.37	0	1321482.0
-149.983	7.55	4214.2	482.40	0	166733.0
-149.995	7.55	4215.4	394.27	0	110684.0
-149.997	7.55	4216.8	967.98	0	740456.0

All transformations only change the coordinates and never the values!

x-shift, y-scale

x	y	λ	value	flag	variance
-95.504	17.325	8408.7	87.72	0	19785.9
-95.503	17.325	8410.0	10.68	0	19655.3
-95.502	17.325	8411.2	43.55	0	20630.6
-95.500	17.325	8412.5	85.31	5	21929.7
-170.482	11.325	4212.9	1281.37	0	1321482.0
-170.483	11.325	4214.2	482.40	0	166733.0
-170.495	11.325	4215.4	394.27	0	110684.0
-170.497	11.325	4216.8	967.98	0	740456.0

astrometric calibration

RA	DEC	λ	value	flag	variance
-19.1008	3.465	8408.7	87.72	0	19785.9
-19.1006	3.465	8410.0	10.68	0	19655.3
-19.1004	3.465	8411.2	43.55	0	20630.6
-19.1000	3.465	8412.5	85.31	5	21929.7
-34.0964	2.265	4212.9	1281.37	0	1321482.0
-34.0966	2.265	4214.2	482.40	0	166733.0
-34.0990	2.265	4215.4	394.27	0	110684.0
-34.0994	2.265	4216.8	967.98	0	740456.0

MUSE Data Reduction

- the "enhanced" approach: **resample only once**!
- transform data from implicit to explicit coordinates ⟶ **pixel table**
- advantages ⟶ revolution
  - accurate error propagation
  - single resampling
  - transformations are faster
- drawbacks ⟶ nuisance
  - computing transformations often more complex and slower
  - the storage / RAM requirements are much higher
  - the final resampling is complex and slow
  - **debugging is a pain!**

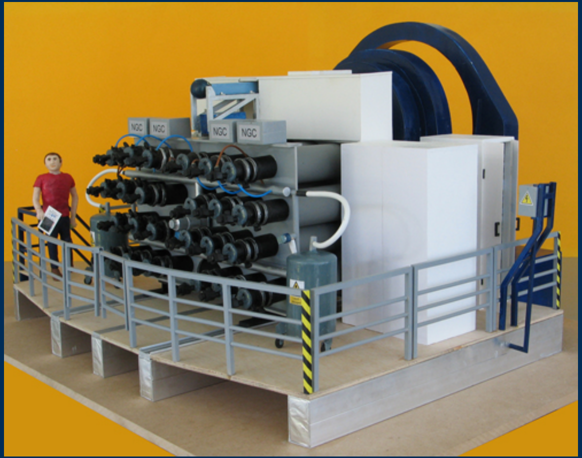
also KMOS!

now also JWST MIRI

MUSE Pipeline Goals

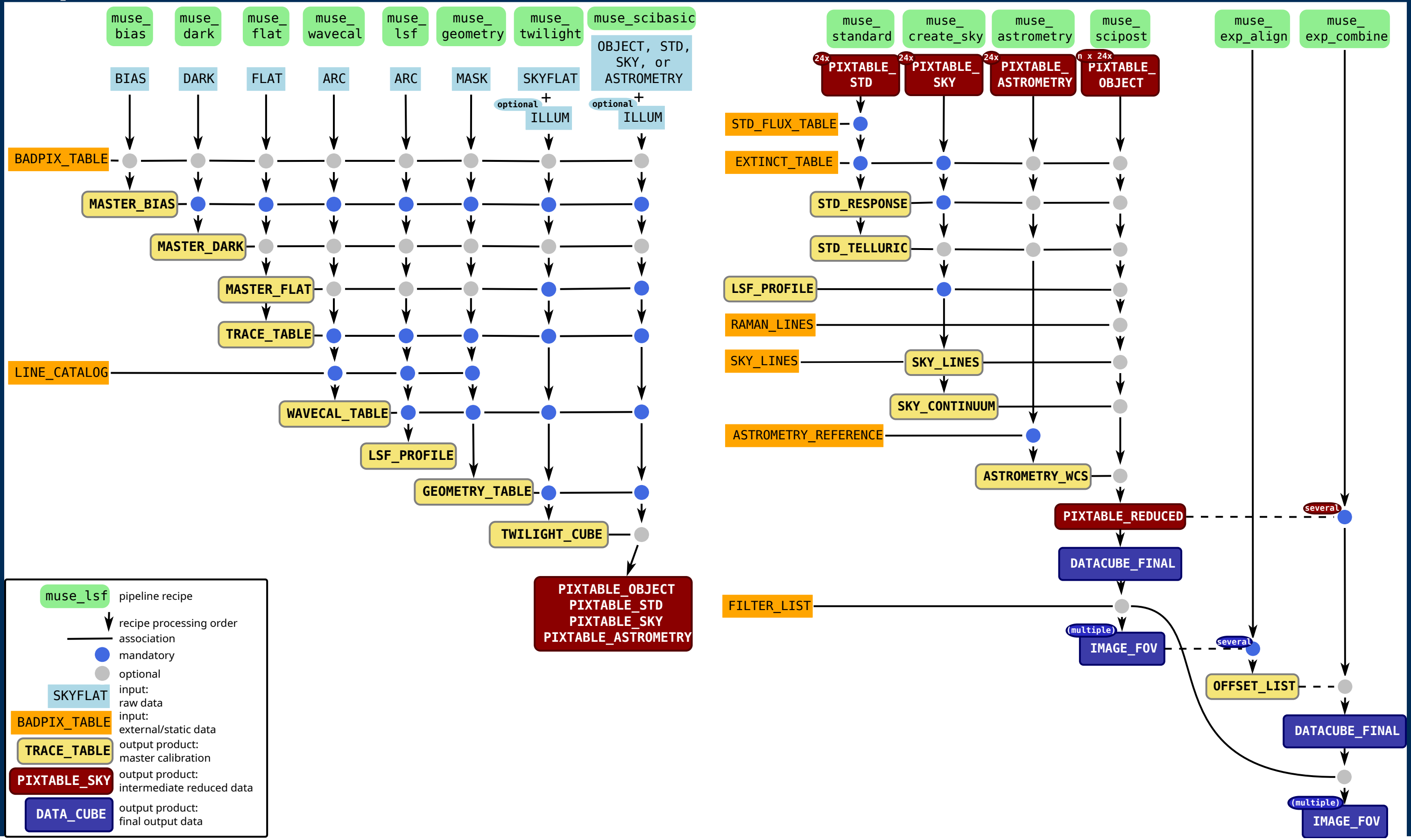
- Transform **raw data** into (scientifically usable) **datacubes** – no higher-level data products
  - Fully reduce all exposures without creating backlog
    - Execution speed, automated operation
  - Knowledge of bad pixels
    - Track bad pixels (and reason) throughout pipeline
  - Propagate error information
    - Compute errors from raw data and propagate variance
  - Minimize rebinning steps
    - Resample only once!
- Decided in 2008 in time for Final Design Review in Jan 2009

MUSE maquette (CRAL 2008?)

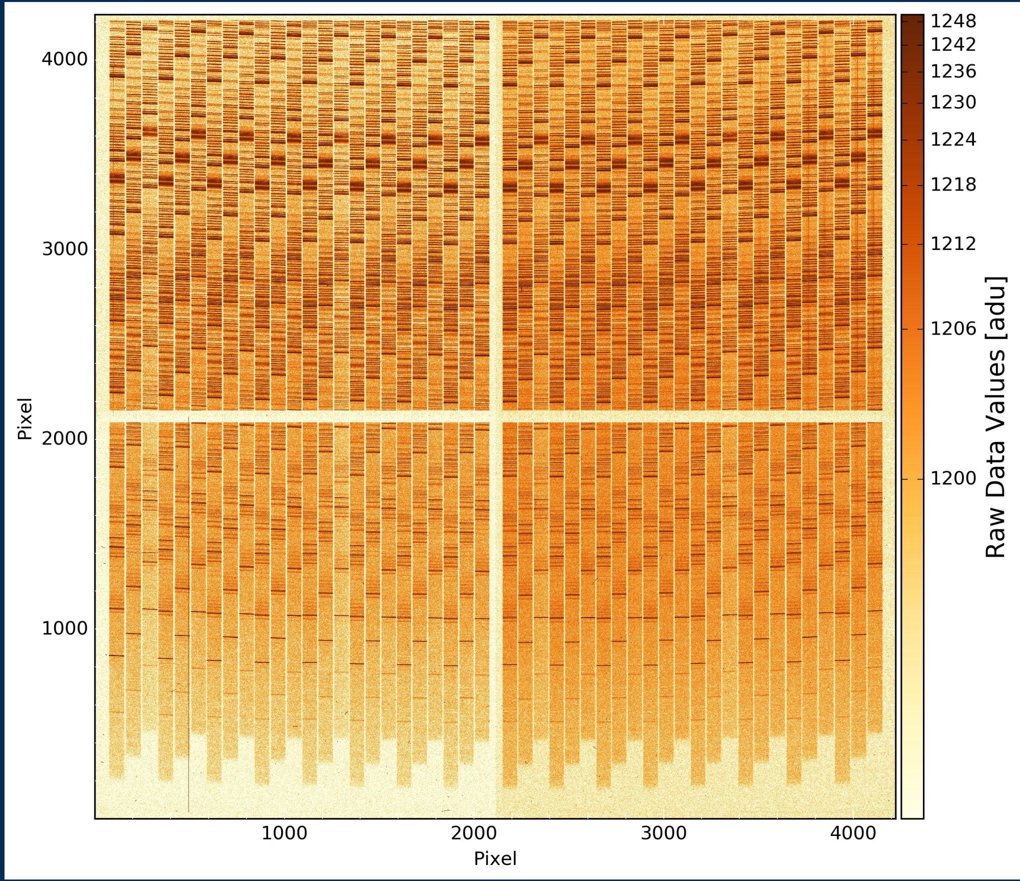


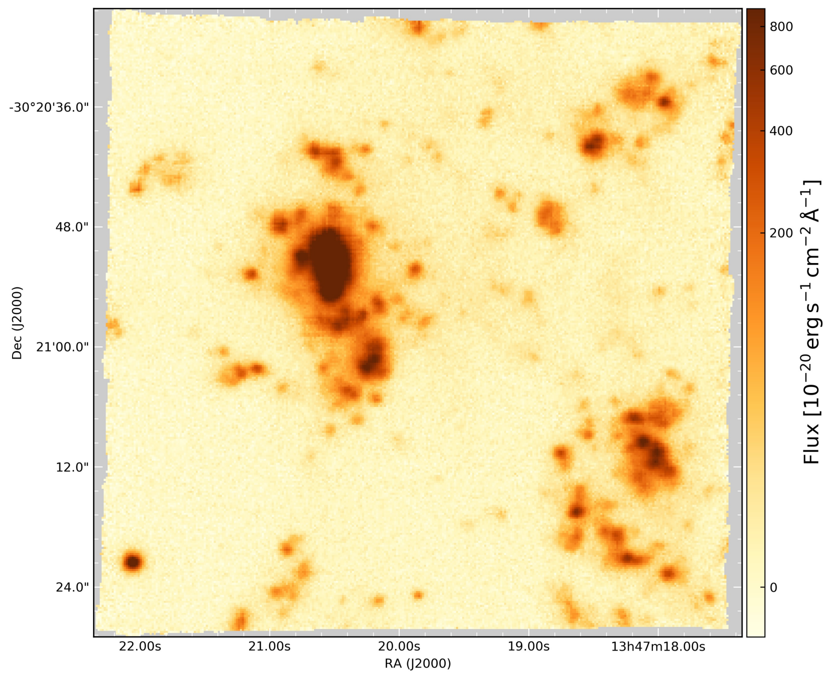
AIP

MUSE Pipeline Structure



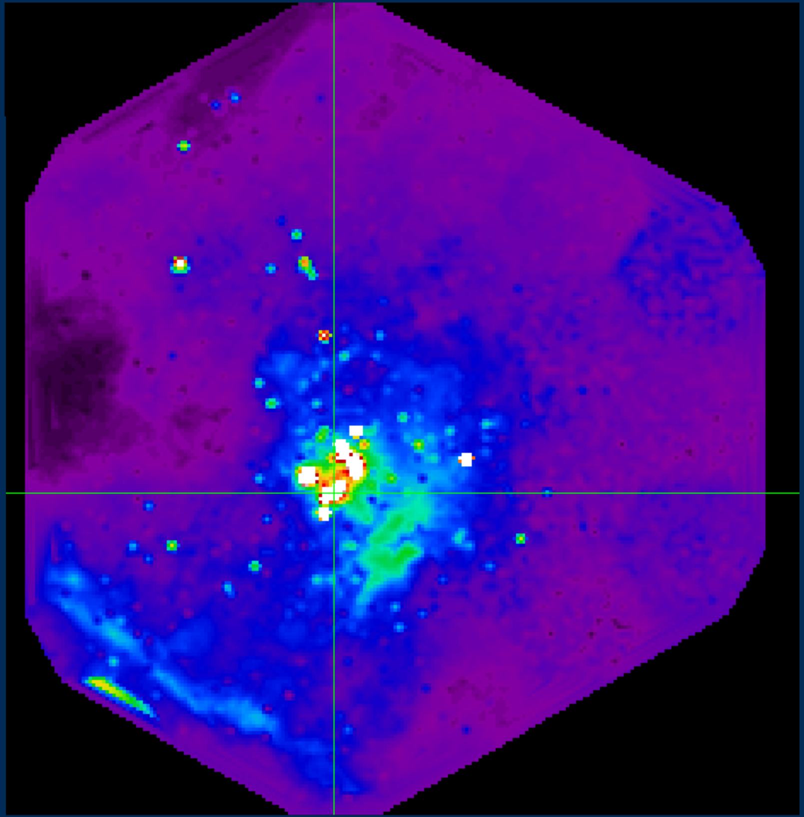
MUSE Pipeline Results





NGC 5291N
three combined exposures at Hα
Fensch et al. 2016 / Weilbacher et al. 2020

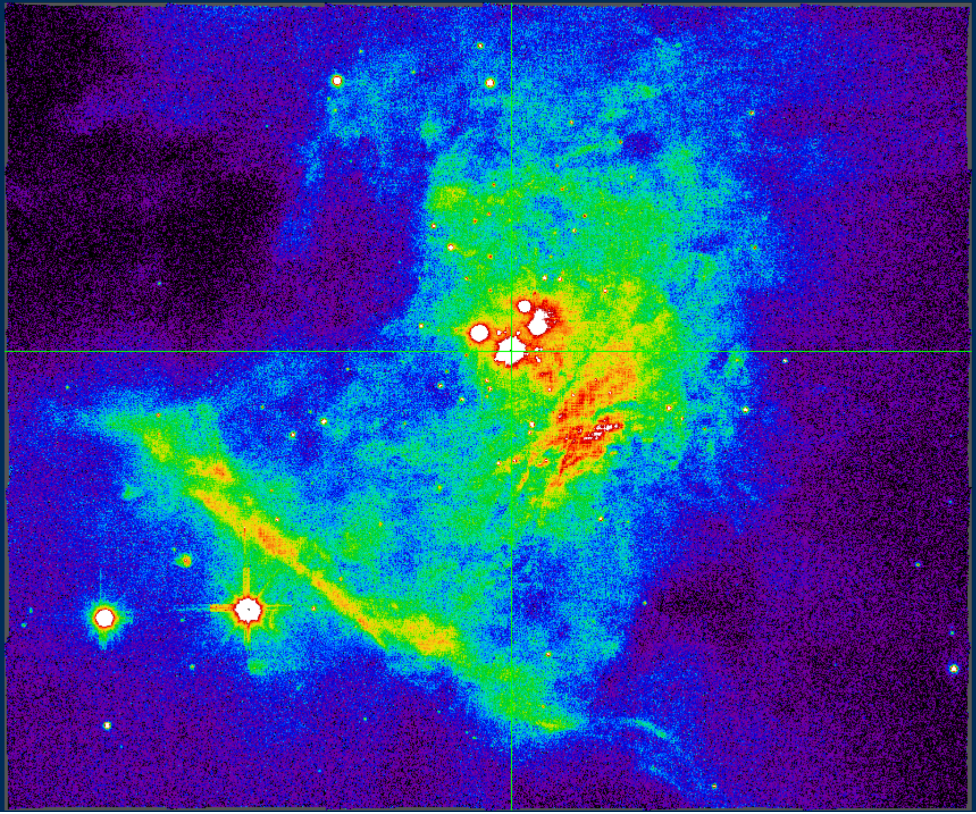
Example: M42

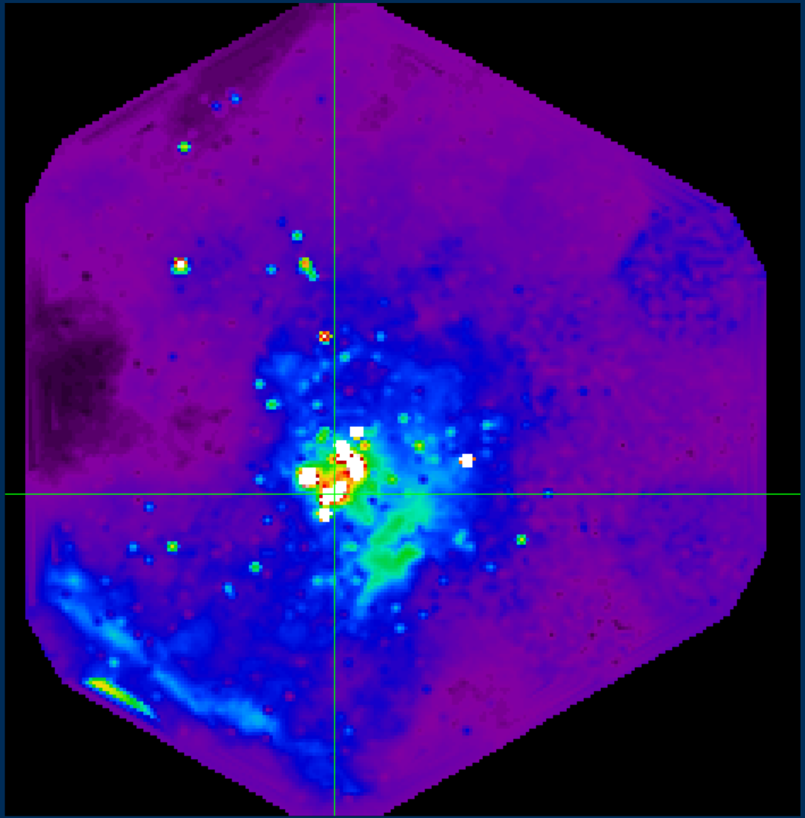


- PMAS/PPak mosaik / 3.5m CAHA
- Sánchez et al. 2007

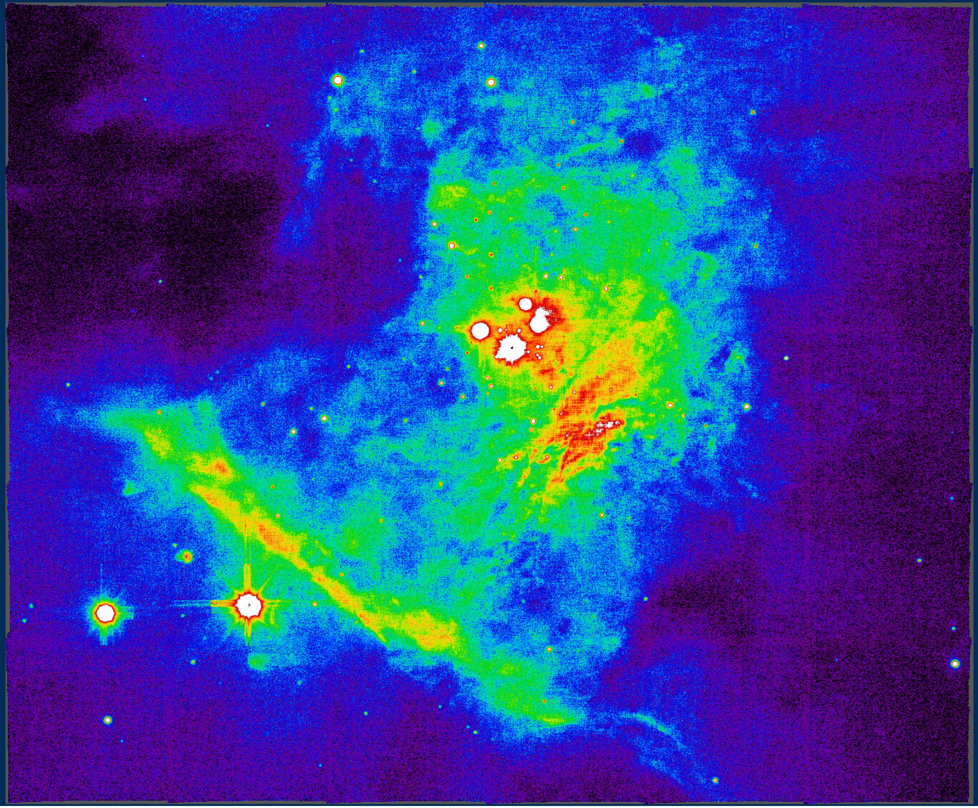
Example: M42

cube plane at ~5755 Å

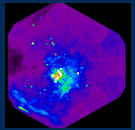




Example: M42

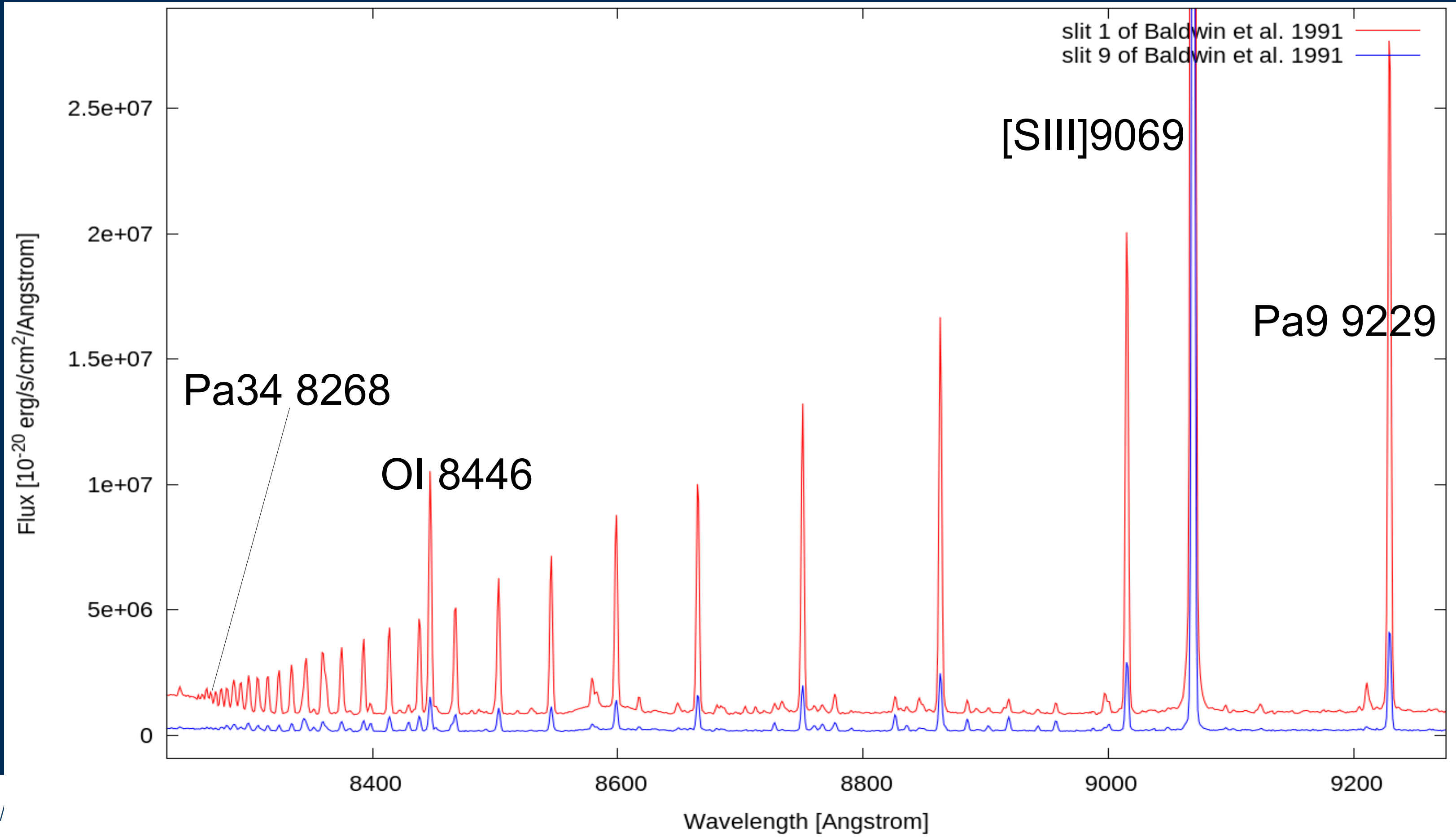


- PMAS/PPak mosaic / 3.5m CAHA
- Sánchez et al. 2007
- 2.7'' spaxels, 65% filling factor
- bad transparency / not photometric
- 27 x 2s, ∼3700–7100 Å
- 235 x 240 x 2120 pixels
- ~9000 spectra



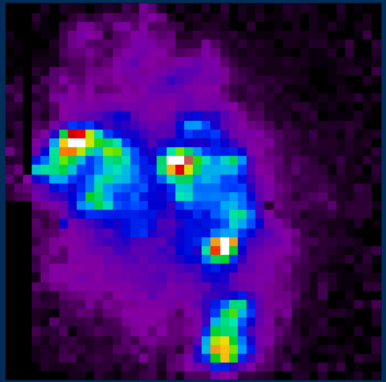
- MUSE mosaic / 8m VLT
- Weilbacher et al. 2015
- ~0.2'' spaxels, contiguous
- clear sky, bright time
- 60 x 5s, 4595 . . . 9366 Å
- 1766 x 1476 x 3818 (or 5614) pix
- 2.5 million spectra

Example: M42

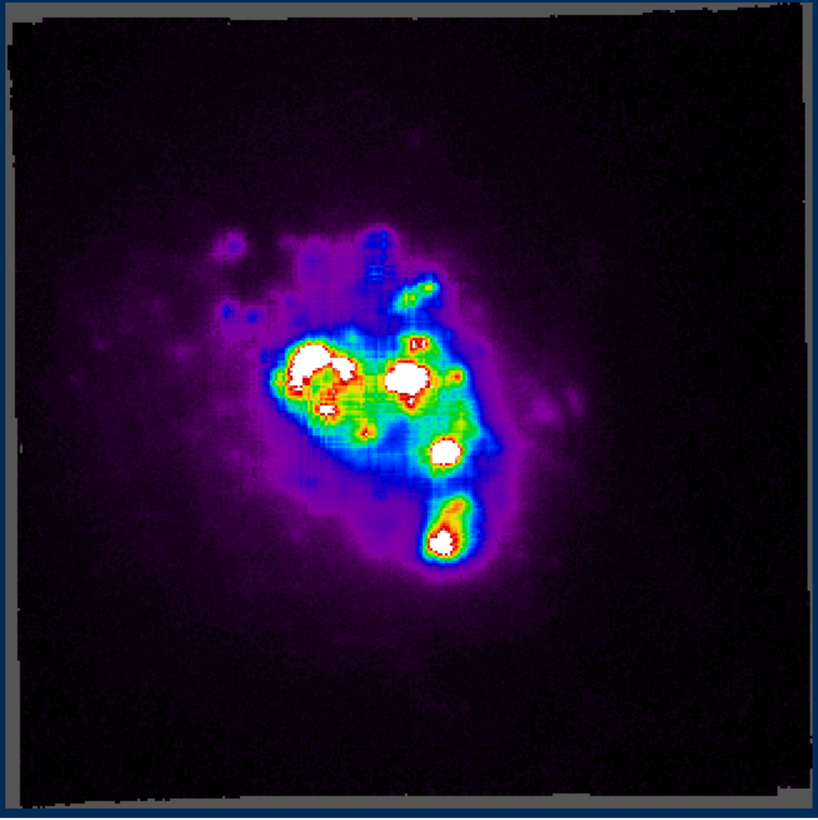

slit 1 of Baldwin et al. 1991
slit 9 of Baldwin et al. 1991
[SIII]9069
Pa9 9229
Pa34 8268
OI 8446
2.5e+07
2e+07
1.5e+07
1e+07
5e+06
0
Flux [10^{-20} erg/s/cm^2/Angstrom]
8400
8600
8800
9000
9200
Wavelength [Angstrom]

Example: Haro 14

- VIMOS cube (Cairós et al. 2015)
  - 0.67'' / spaxel (2 modes, here: orange)
  - 1.2h (6 exposures)
  - reduction Aug. 2007 to July 2011
    → Paper subm. Aug. 2013



- MUSE cube (Cairós et al. 2021, 2022)
  - ~0.2'' spaxels (1 mode WFM-AO-N)
  - 1.5h (4 exposures), SV data
  - reduction Sept. 17th to 18th, 2017
    (refined again March 2019)
    → Paper subm. Jan. 2021



→ revolution?

How did we get there?

- Data reduction worked *out of the box* for *many* datasets, in July 2014:
  - esorex + scripts
  - Reflex

- instrument stability / predictability
- early testing, with simulated and real data
- maintain the pipeline in collaboration with ESO
- manpower / (GTO) community involvement

People

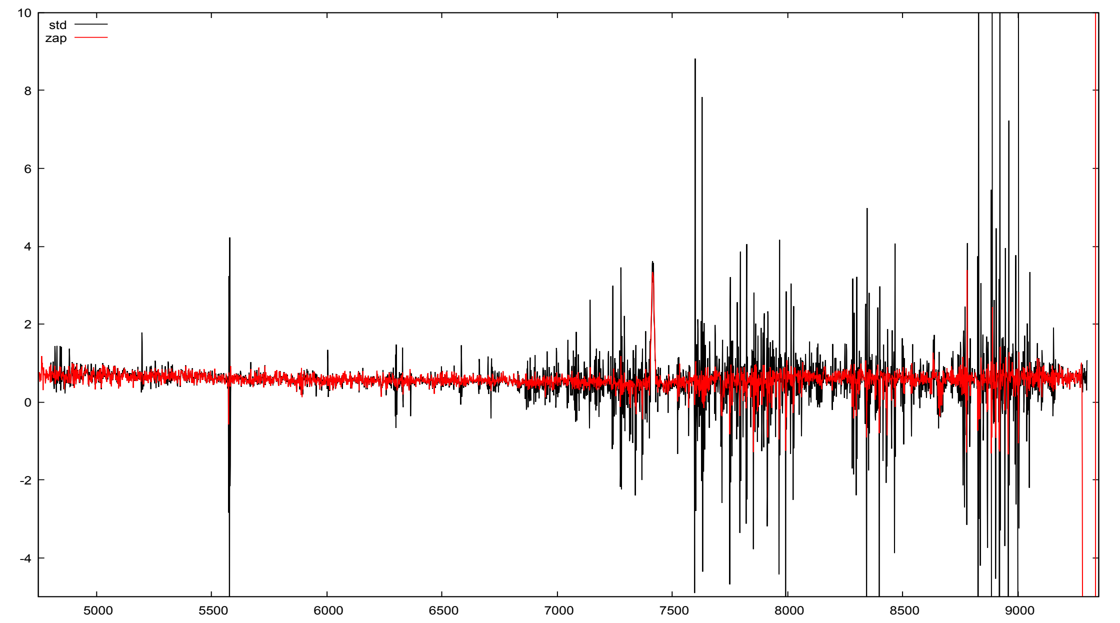
- 2 dedicated developers (PMW + Ole Streicher)
- 1 serious tester (Tanya Urrutia), also wrote initial pipeline manual
- GTO team:
  - 1 PI eager to test
  - 5+ people who ran the pipeline on simulated data
  - 20+ people who looked at data from 1st commissioning
- 1 very helpful ESO pipeline contact (Ralf Palsa)
  - wrote the (online) "pipeline"
  - developed the `muse_exp_align` recipe
- many more people who contributed in various ways!

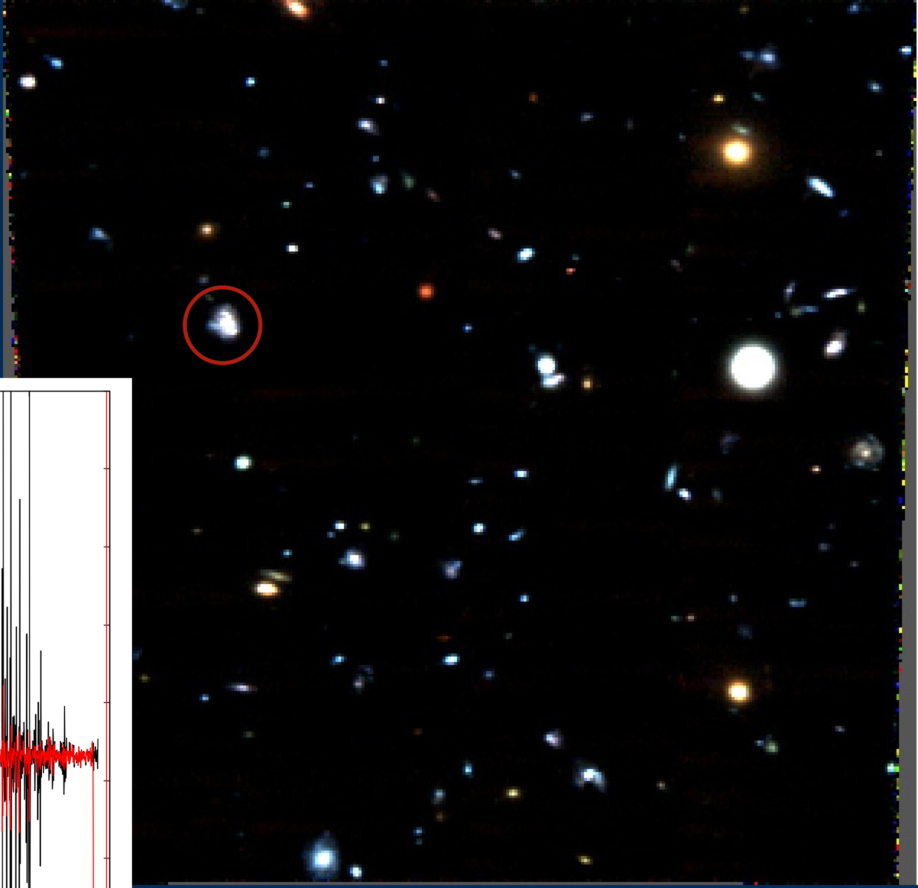
Only one pipeline

- we never had any ”consortium“ version of the pipeline
- maintenance at AIP until v2.8.3 (June 2020)
- close collaboration between AIP and ESO
- most analysis tools (MPDAF) from GTO team were also made public

Testing

- Instrument Numerical Model (INM, Aurélien Jarno)
  - multiple simulated “Dry Runs“
  - reduction with different options in the GTO team





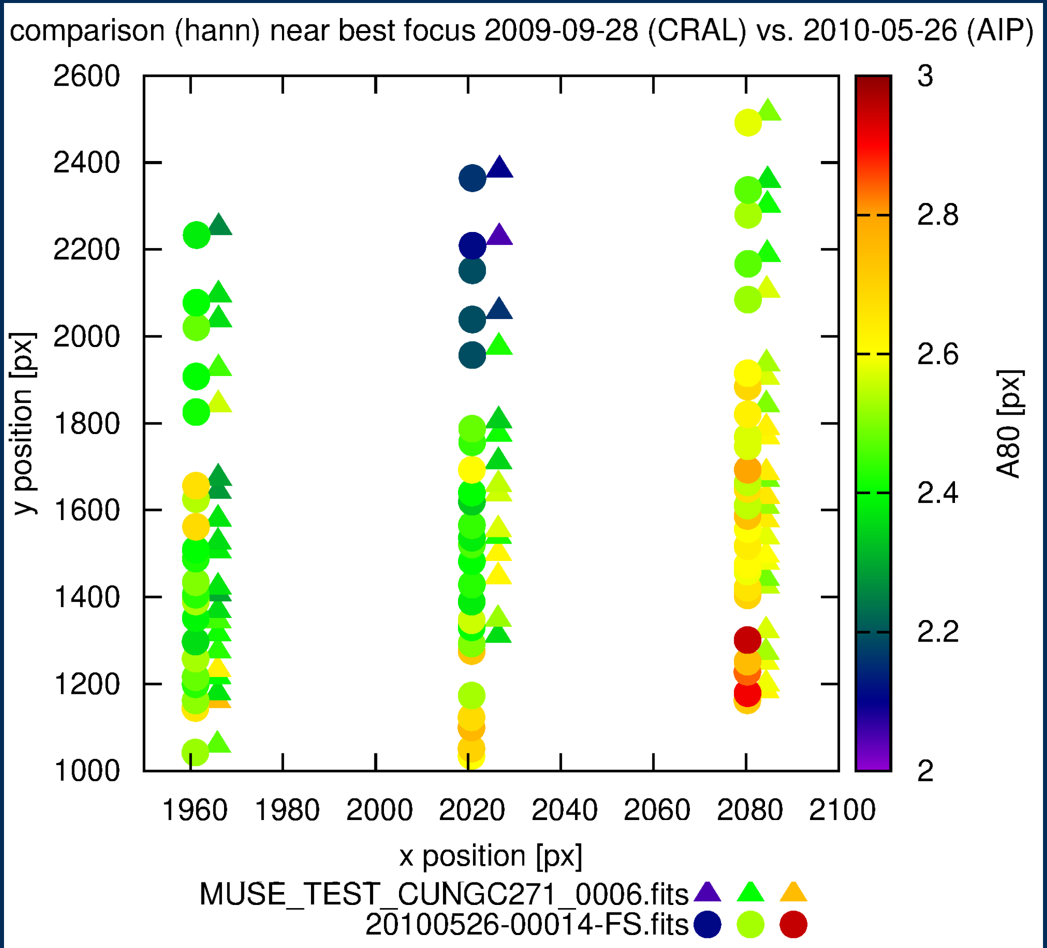
Testing

- Instrument Numerical Model (INM, Aurélien Jarno)
  - multiple simulated “Dry Runs“
  - reduction with different options in the GTO team

  - but also: bug in INM or the pipeline?
  - non-optimal sky model
  - orientation (DAR correction)

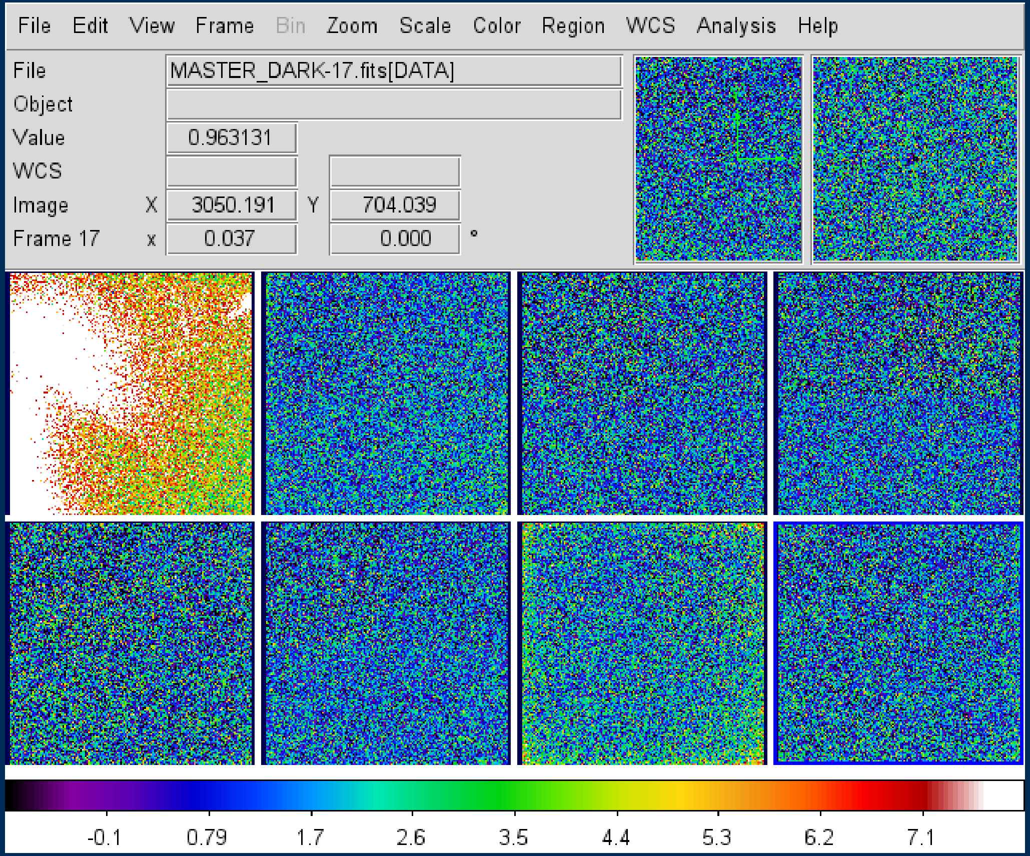
Testing

- Instrument Numerical Model (INM)
- Lab data
  - detector focus testing at AIP



Testing

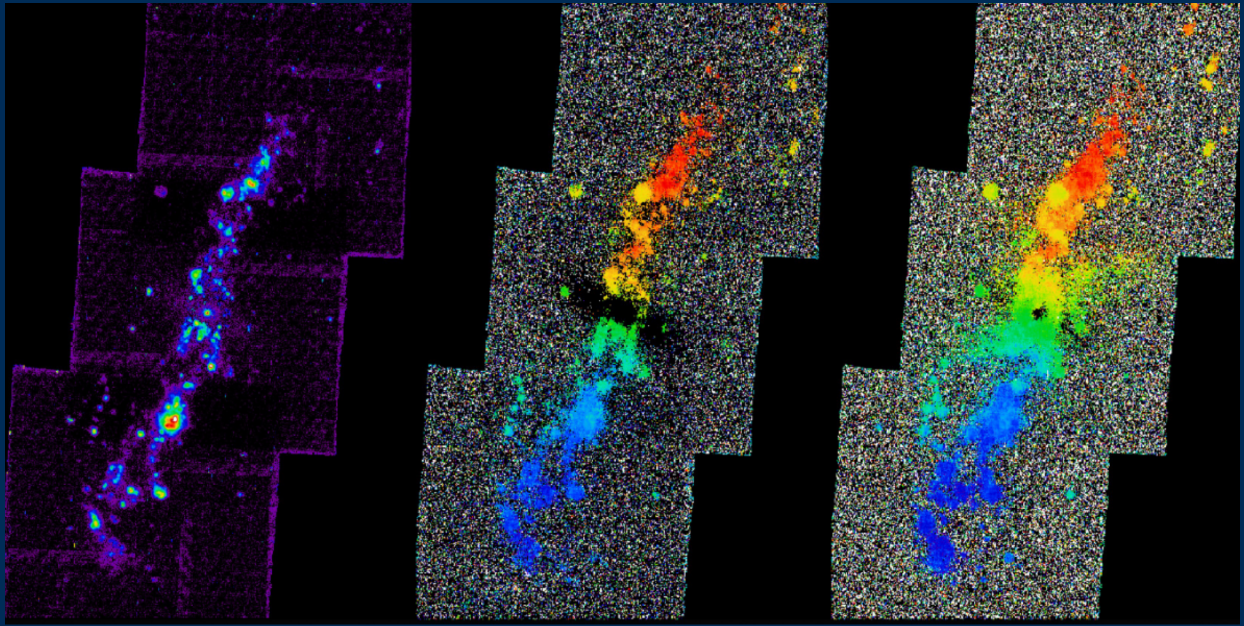
- Instrument Numerical Model (INM)
- Lab data
  - detector focus testing at AIP
  - various calibration exposures from ESO, CRAL, and AIP



Testing

- Instrument Numerical Model (INM)
- Lab data
- Commissioning data
  - many different datasets
  - calibrations and
    on-sky exposures

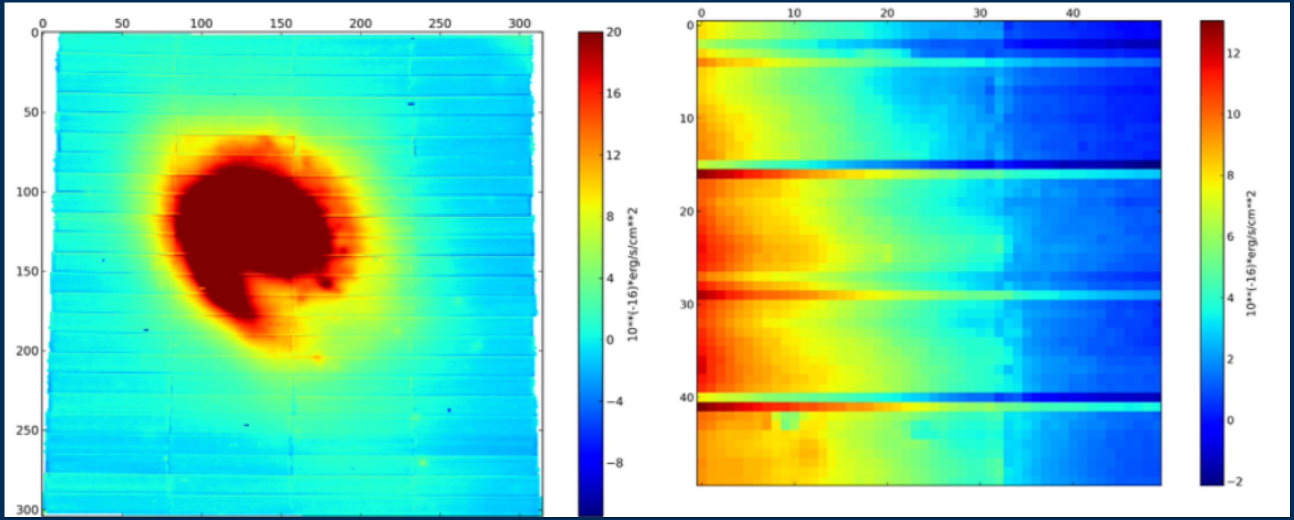
NGC 4650A
later published (Iodice et al. 2015)



Testing

- Instrument Numerical Model (INM)
- Lab data
- Commissioning data
  - many different datasets
  - calibrations and
    on-sky exposures

IRAS 05177
Stolarsky & Shirazi and Carollo



Testing

- Instrument Numerical Model (INM)
- Lab data
- Commissioning data
- Automated testing
  - Unit tests
  - Weekly automated reductions

Calibrating instrument behavior

- Telluric sky emission for wavelength zeropoint correction
  - offsets for each IFU
  - early commissioning (pipeline v0.18.0, in time for SV)
- ILLUM flats
  - flux factors for each slice
  - late commissioning, after 1st science verification (v1.0, Dec. 2014)
- Slice autocalibration
  - flux factors for several wavelength ranges within each slice
  - first tested in MPDAF (v1.1.14, Jan. 2015), then re-implemented in pipeline (v2.4, March 2018)
- Superflat
  - 3D correction, factors for each cube voxel
  - external tools + pipeline (v2.4, March 2018)
  - fully realized for 2nd deep field processing (MXDF)

Where did we fail?

- Sky subtraction → ZAP, CubePCA, ...
- Flat-fielding
- Offset / distortion correction (for combination at cube level?)
- Response curves: flux calibration fails surprisingly often!
- Did not provide (Python-based) data management
  many Python wrappers written by users (python-cpl, MuseWise, musered, Aoide, pymusepipe, ...)
  now EDPS

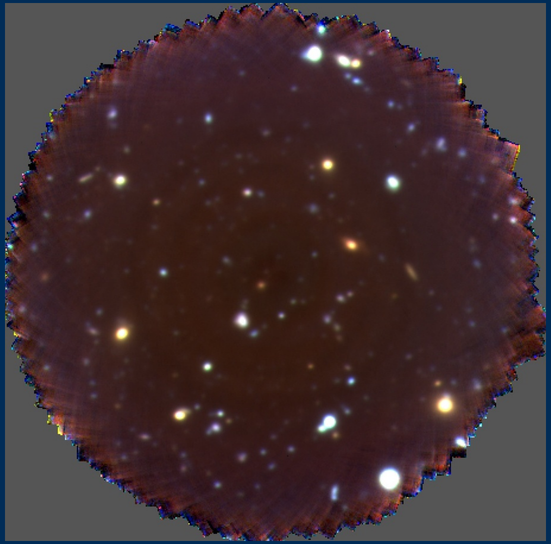
→ nuisance!

- involvement of other people with pipeline was often superficial
  - external workarounds (e.g., ZAP, CubEx, ...) rather than adaptation of pipeline

Ready-made MUSE cubes

- IFU surveys
  - CALIFA: DR1, 100 objects (2012) ⟶ DR3 646 galaxies (2016)
  - SAMI: early DR, 107 galaxies (July 2014) ⟶ DR3 3068 galaxies (2021)
  - SDSS MaNGA: DR15, 4824 cubes (2018-12-10) ⟶ DR17 11273 cubes (2021-12-06)
- MUSE IDP production at ESO
  - 1st (and only?) IFU to get provide reduced data (cubes!) directly to the users
  - started in 2015 (⟶ Reinhard Hanuschik, Danuta Dobrzycka)
  - the 1st **2000 cubes** were released on 2016-06-22
  - ⟶ revolution
- Cubes now also available from other IFUs
  (e.g. Keck, OSIRIS and KCWI, but only single exposures?)
- MUSE data products now:
  - MUSE collection (single OB): ~16000 cubes
  - ~1500 cubes in MUSE-DEEP collection (multi-OB combinations)

MXDF (ESO archive cube!)
V,R,I color image

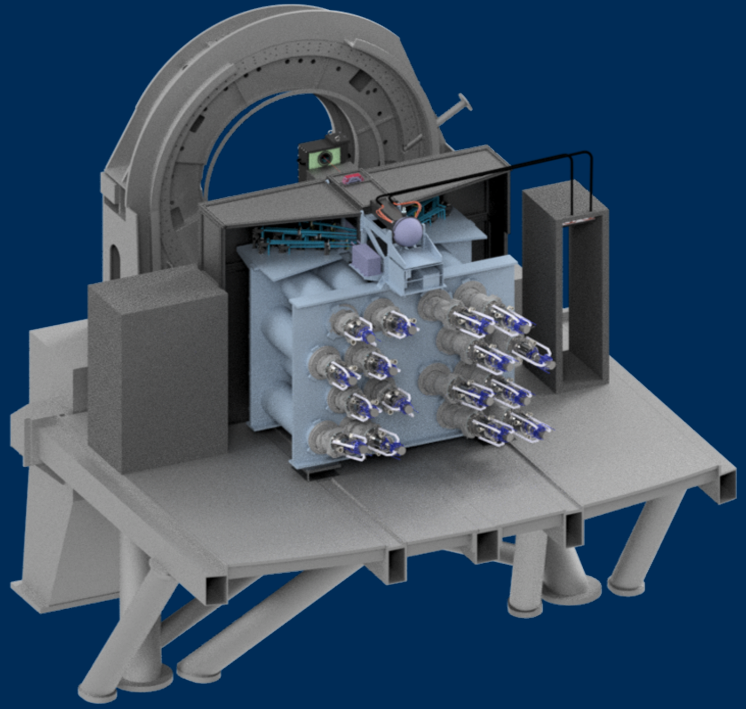


Future I

BLUE MUSE
multi unit spectroscopic explorer

PI: Johan Richard (CRAL)

Telescope	one of the VLT UTs
Instrument Type	Optical Integral Field Spectrograph
Wavelength range	about 350 – 580 nm
Resolution	R ~ 2600 – 4200 ~2x MUSE
Field of view	contiguous, ~1' x 1'
Detectors	16 CCDs (4k x 4k)
Sampling	0.2'' x 0.3'' x 0.06 nm
Throughput (incl. telesc. & atmosph.)	35% (18% at blue end)
Commissioning	2031 ESO-Phase A started June 2024
AO support	None

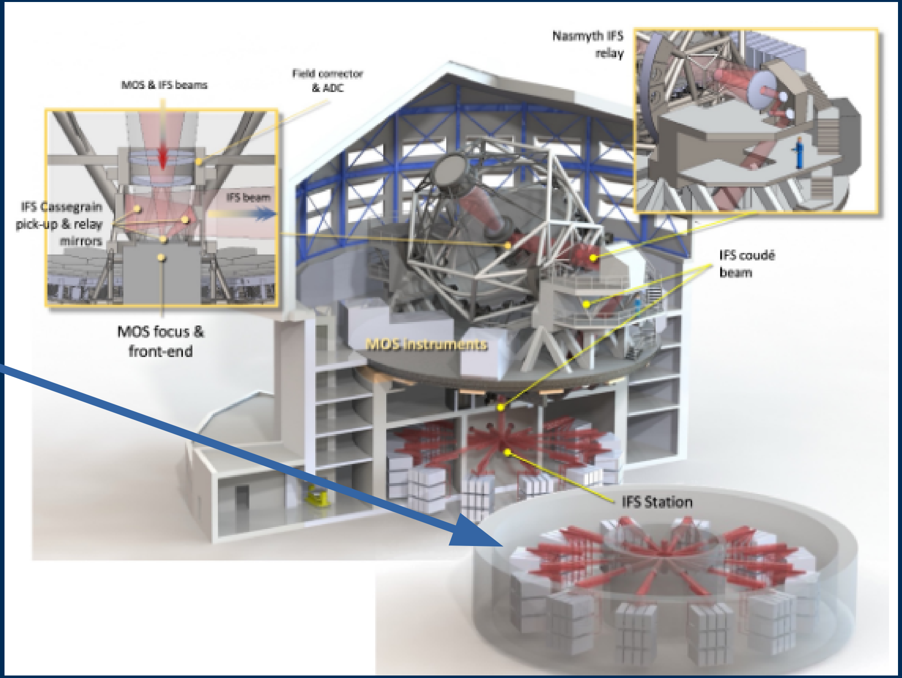


Pipeline / Data Reduction Software to be developed in Germany, led by AIP

Future II

- MOS + IFS
- MUSE-like integral field spectrograph with contiguous 9 $arcmin^2$ field of view
- full optical wavelength coverage
- **144 spectrographs for IFS!**
- survey mode
  ⟶ huge amount of data
  ⇒ quick reduction necessary

Lee et al. 2405.19198



Future III: general ideas

- more pipeline features
    - covariance

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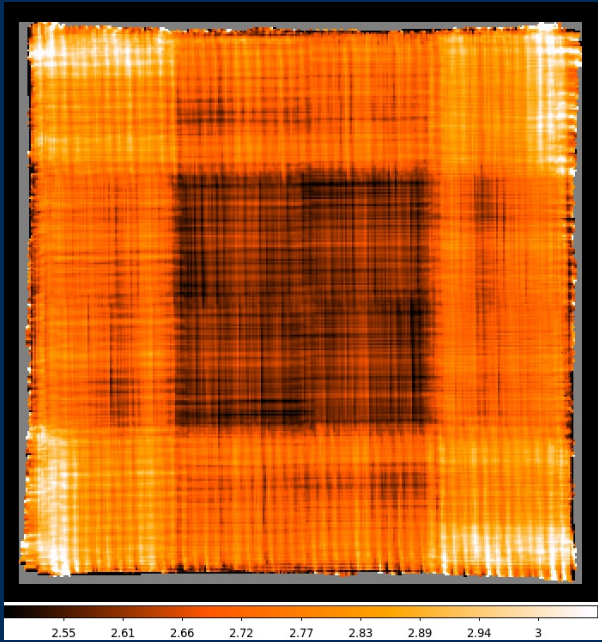
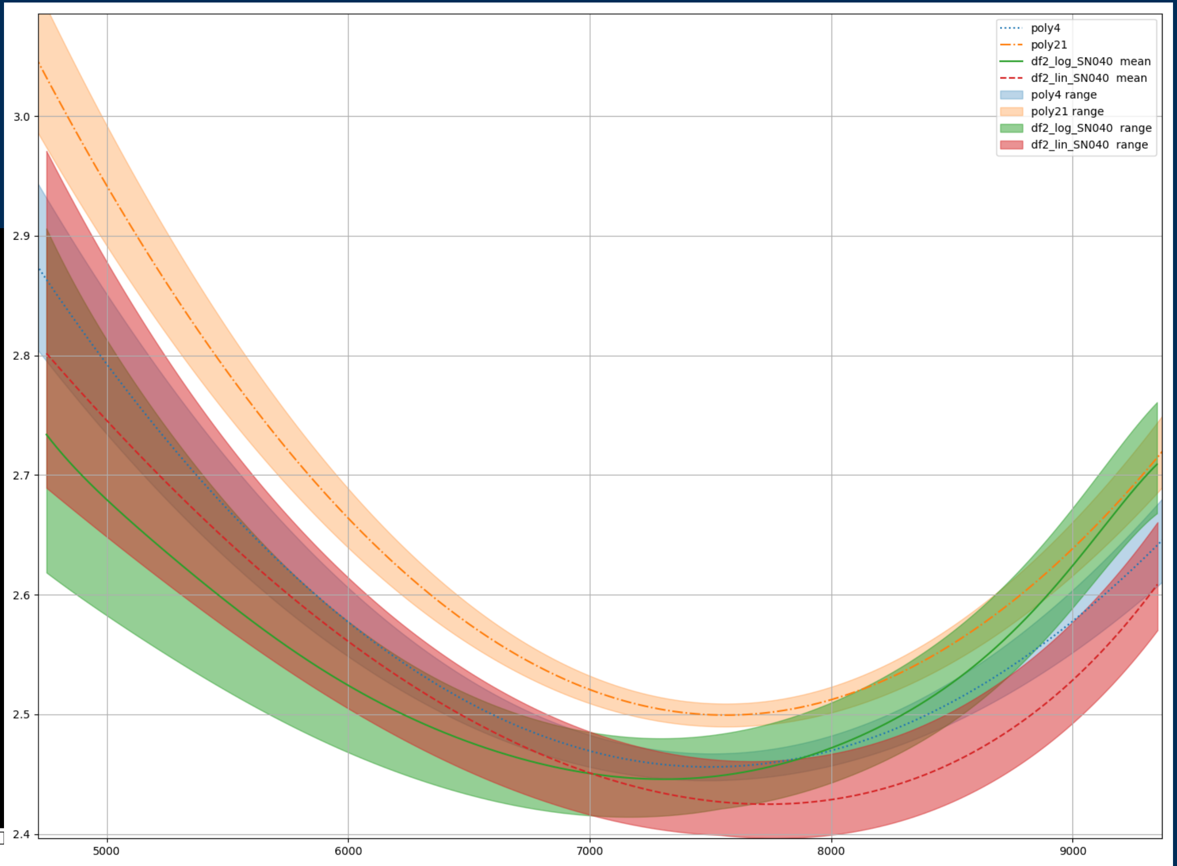
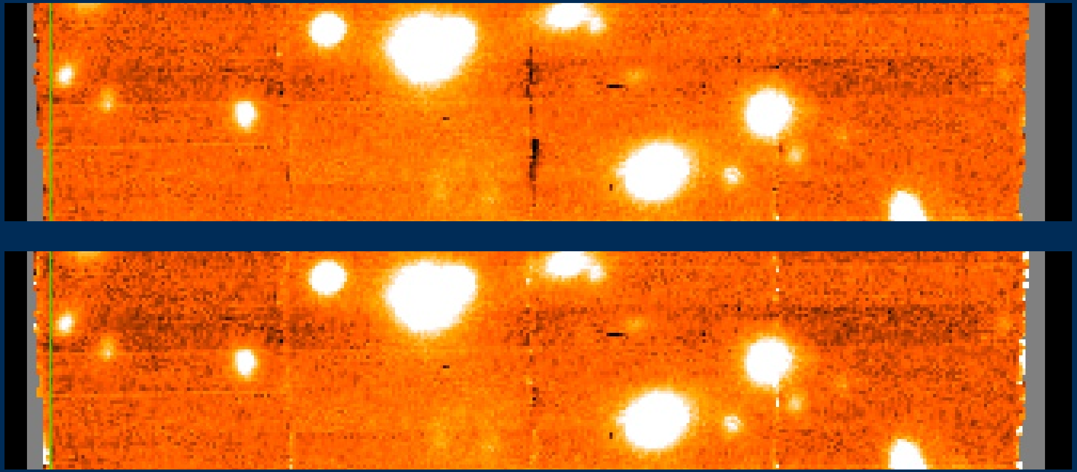
- more pipeline features
  - covariance
  - propagated LSF





Future III: general ideas

- more pipeline features
  - covariance
  - propagated LSF
- better/faster data reduction / cube production
  - lower level of artifacts, better sky subtraction, more accurate flat-fielding, ...



Future III: general ideas

- more pipeline features
  - covariance
  - propagated LSF
- better/faster data reduction / cube production
  - lower level of artifacts, better sky subtraction, more accurate flat-fielding, … (→ Data Challenge)
  - faster processing, more parallelization
  - use GPUs for processing? – portability?!
- data organization / storage
  - faster I/O (file formats?)
  - in-memory processing
- different reduction paradigm?
  - machine learning: train with raw MUSE data and corresponding well-reduced cubes
  - get machine-written optimized code for the reduction

Conclusions

- MUSE data reduction set new standard for IFS data processing
  - easy to use (with Reflex: click one button)
  - quick to get *acceptable* results → ready-made cubes in ESO archive!
  - involvement with simulated and lab data helped to catch (some) problems early!
- Annoying artifacts remain in default data reduction
  - workarounds exist (ZAP, superflats)
  - difficult to apply, except for empty fields
- Future
  - possibility to get even better calibrations and new features
  - (how) will machine-learning help?
  - new instruments BLUE MUSE and WST → processing options to be designed/studied in the next years

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The End