Introduction to integral-field spectroscopy

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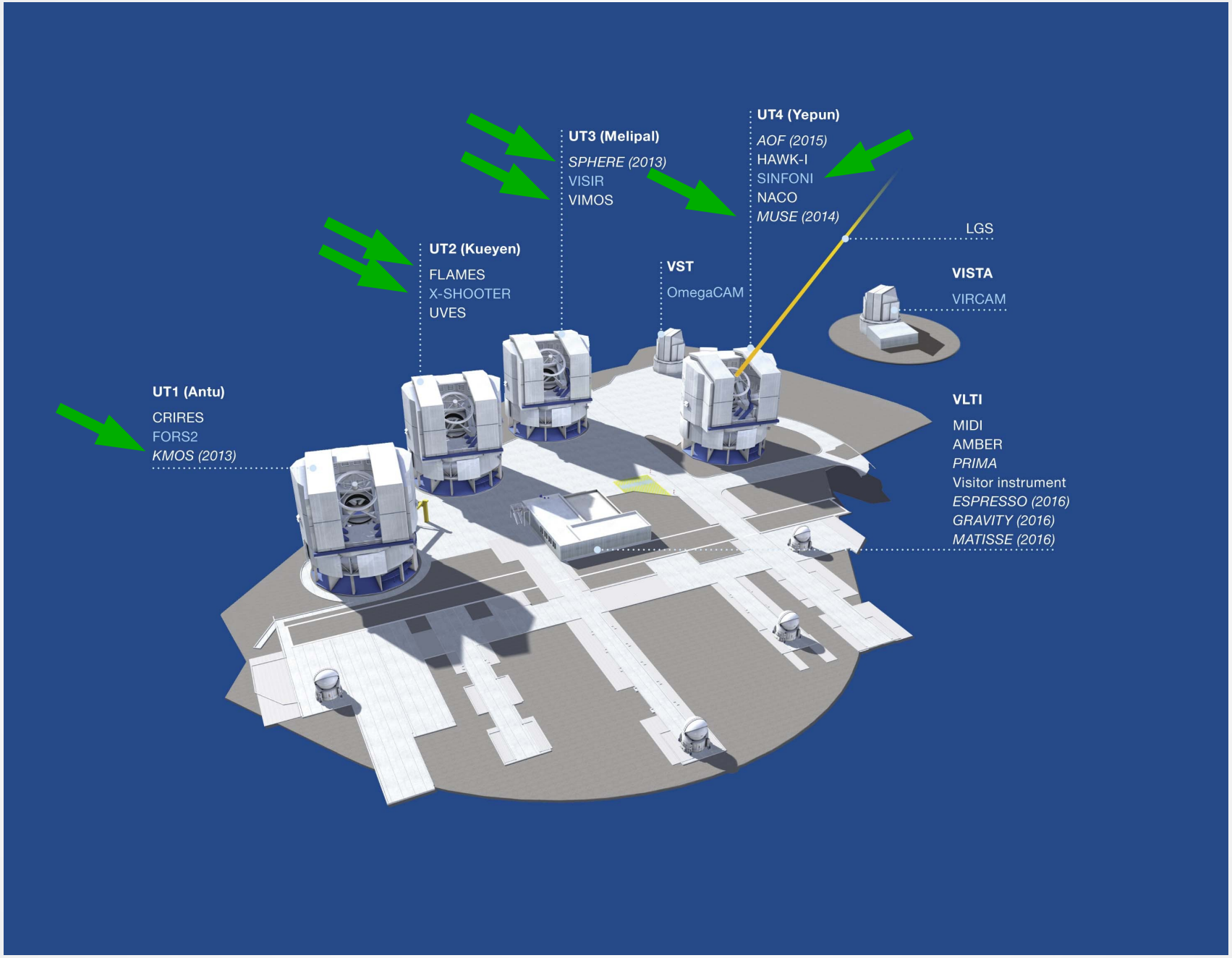
The importance of IFS



The importance of IFS

ann15070 — Announcement

Agreement Signed for E-ELT HARMONI Instrument

23 September 2015

ESO has signed an agreement with an international consortium of institutes [1] for the design and construction c
HARMONI instrument for the European Extremely Large Telescope (E-ELT).

The agreement was signed by Grahame Blair, Executive Director of Programmes, Science and Technology Faci
Council, on behalf of the consortium, and Tim de Zeeuw, ESO Director General, at a ceremony at the Mathema
Institute, University of Oxford, United Kingdom, on 22 September 2015.

Patrick Roche, President of ESO Council and Niranjan Thatte, Principal Investigator for HARMONI, were also in
attendance.

HARMONI, or the High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph, will b
the first-light instruments installed on the giant telescope and will function as the workhorse instrument for visible
near-infrared spectroscopy in the wavelength range 0.5–2.4 µm. It can work with different adaptive optics syste
even without adaptive optics at all, and will complement the MICADO camera, which is primarily focused on ima

Search...

About the Announcement

Id: ann15070

Images

ann15073 — Announcement

Agreement Signed for METIS Instrument for E-ELT

28 September 2015

ESO has signed an agreement with a consortium of institutes around Europe [1] for the design and construction of METIS, an infrared camera and spectrograph for the European Extremely Large Telescope (E-ELT).

The agreement was signed by H. W. (Willem) te Beest, Vice-President Executive Board, Leiden University, on behalf of the consortium, and Tim de Zeeuw, ESO Director General, at a ceremony at the Science Faculty Club of Leiden University in the Netherlands, on 28 September 2015.

Bernhard Brandl, the Principal Investigator of METIS, was also in attendance as well as all Co-Investigators and the project managers of all the partners in the consortium.

METIS is one of the Phase 1 instruments for the E-ELT. It will offer imaging and medium-resolution spectroscopy over a wavelength range from 3–19 micrometres, and high-resolution integral field spectroscopy over a wavelength range of 3–5.3 micrometres. METIS is the only E-ELT Phase 1 instrument to work at these longer mid-infrared wavelengths and complements the MICADO camera and HARMONI spectrograph.

The METIS instrument, in conjunction with the huge light-collecting power and resolution of the E-ELT, will allow many

Search...

About the Announcement

Id: ann15073

Images

PR Image ann15073a
Agreement Signed for METIS Instrument for E-ELT

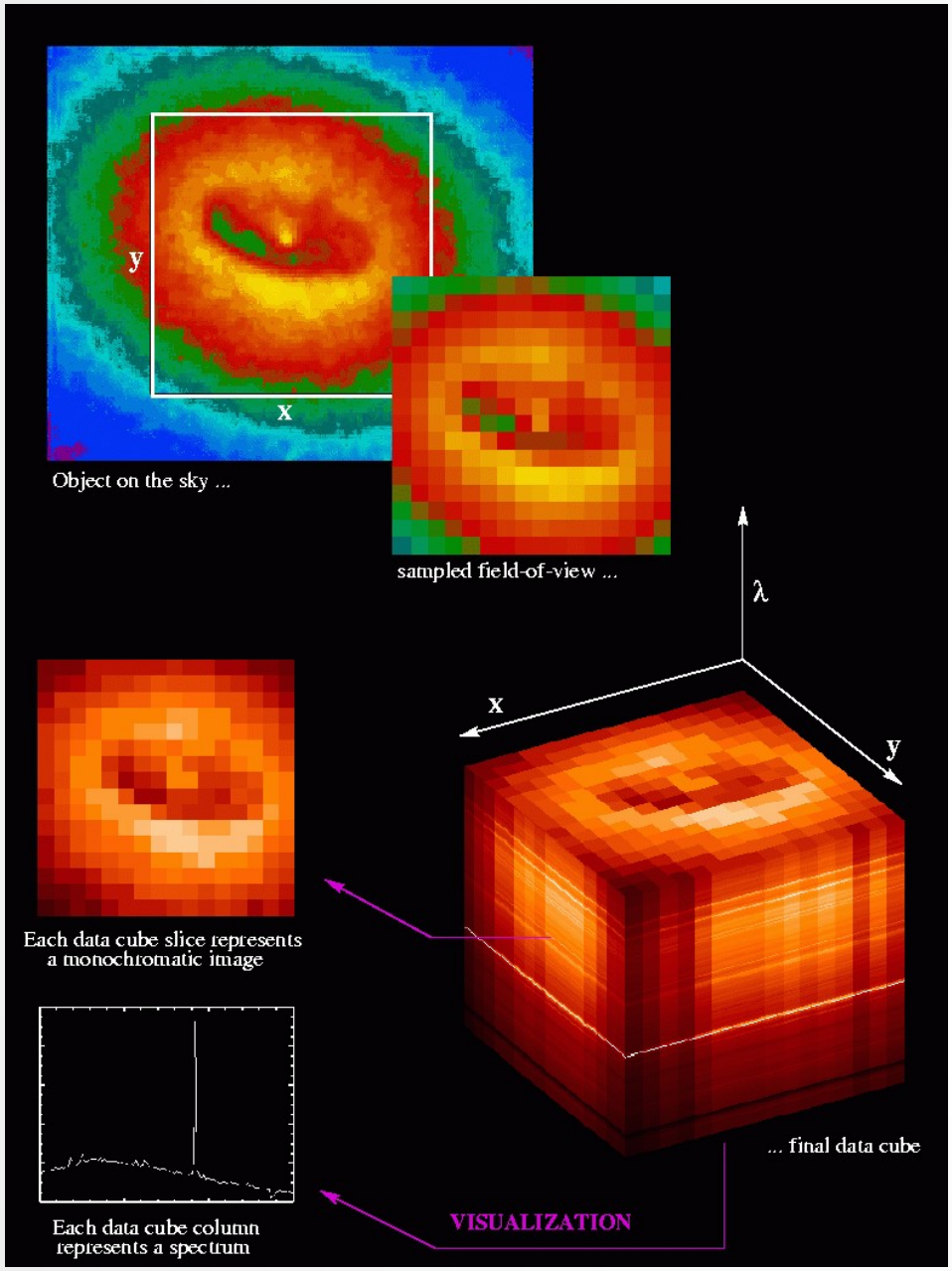
PR Image ann15073b
Agreement Signed for METIS Instrument for E-ELT

PR Image ann15073c
Agreement Signed for METIS Instrument for E-ELT

Outline

- Idea of integral field spectroscopy
- Advantages of IFS
- Instrument design
- Selection of scientific applications
- Challenges of IFS
- Tipps & Tricks & Tools
- Student homework!

The idea of integral-field spectroscopy



credit: M. M. Roth

- combine imaging and spectroscopy
- „3D spectroscopy“
- output: datacube
  - 2 spatial dimensions
  - 1 spectral dimension
- complex instrument structure

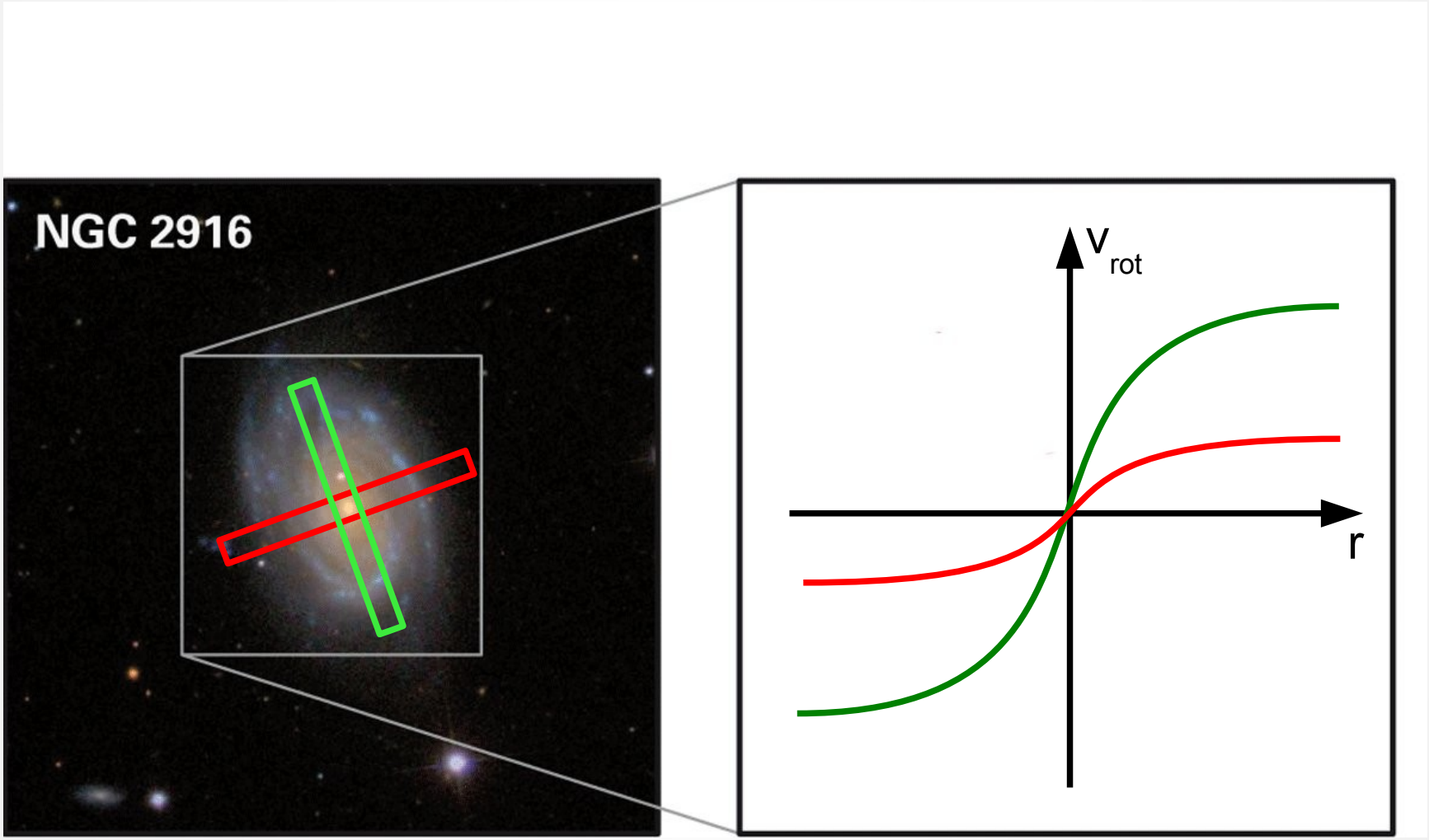
Navigating through a cube

- Some definitions:
  - pixel – a datapoint on a CCD
  - spaxel – a spectrum in a datacube
  - voxel – a datapoint in a datacube

  - „A spaxel consists of many voxels...“

Advantages of IFS

- Observe the whole object



credit: CALIFA team, M. Lyubenova

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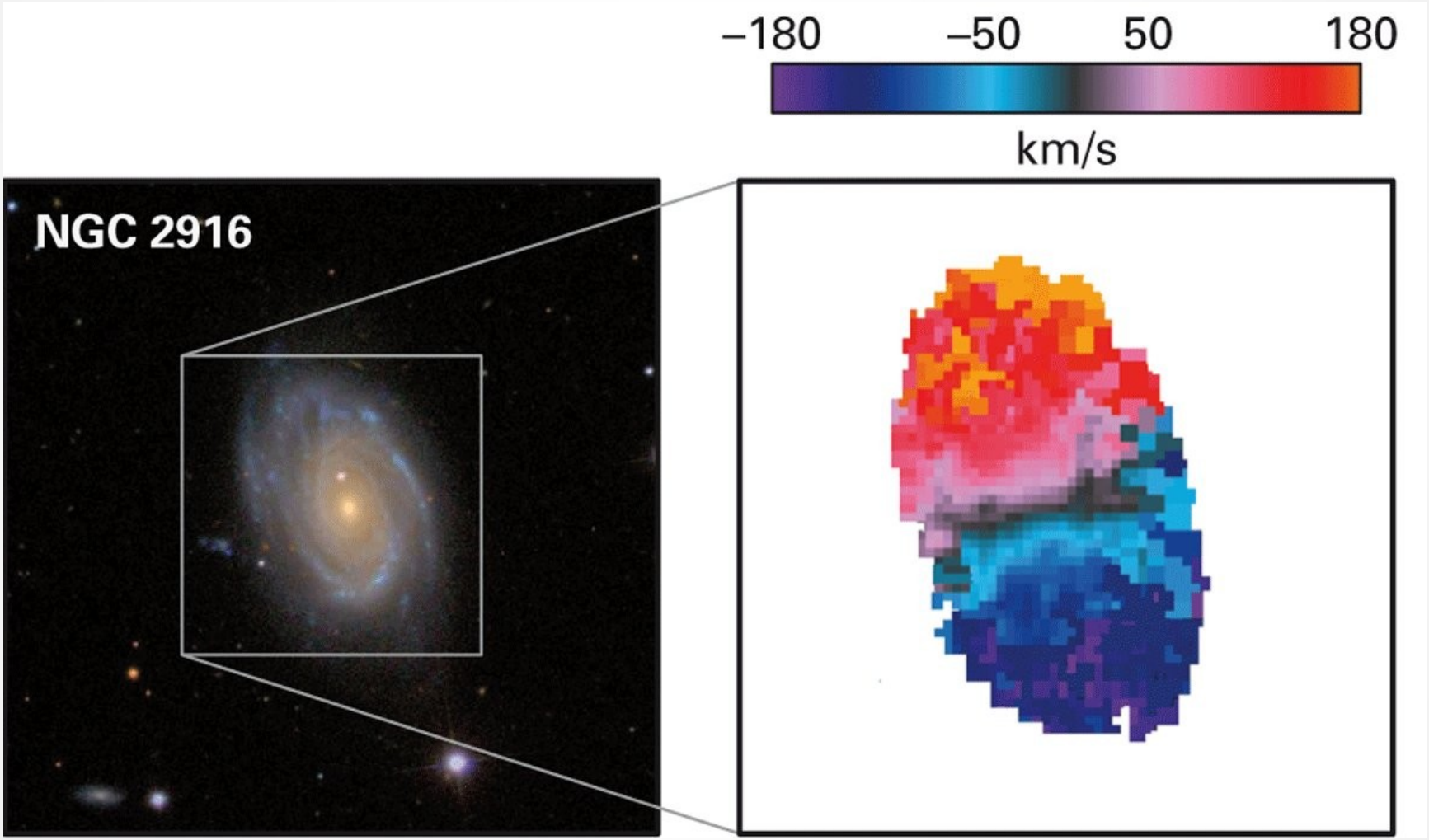
- Observe the whole object



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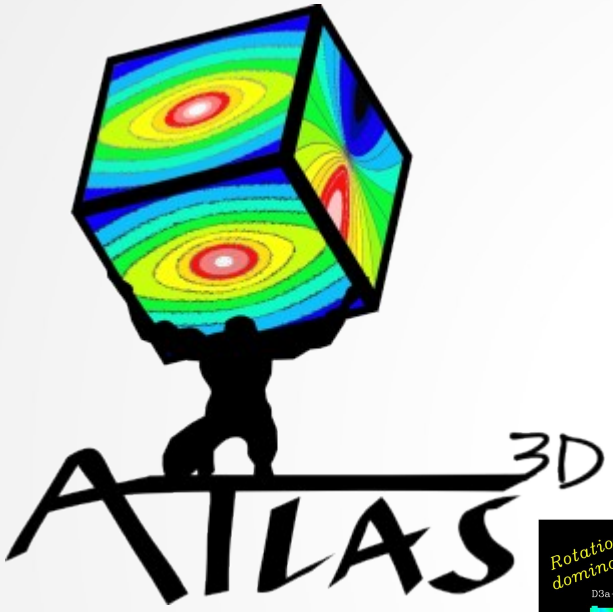

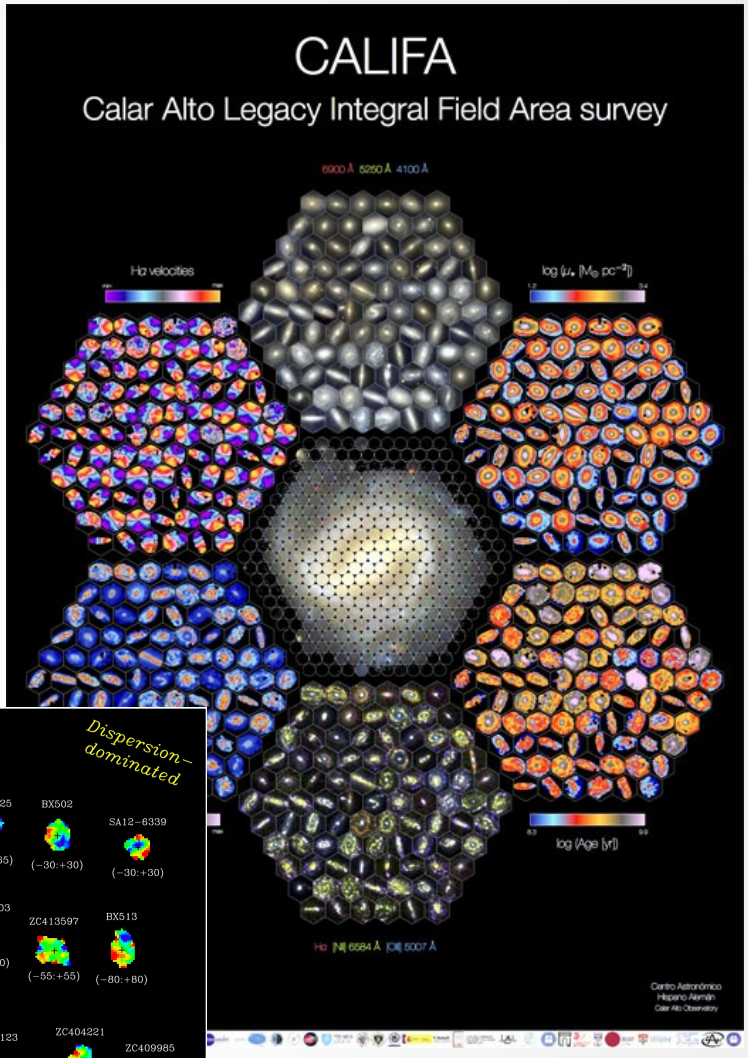

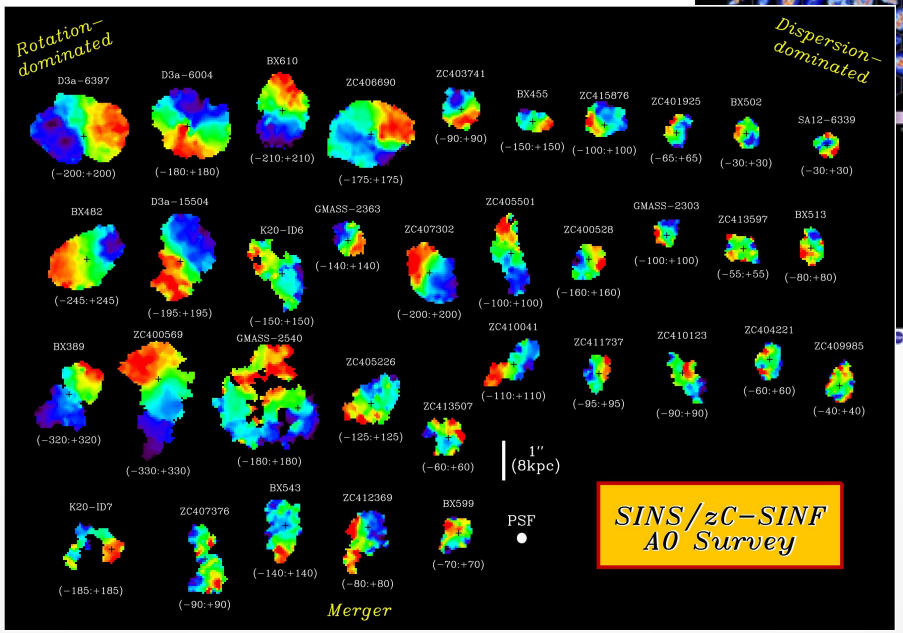

credit: Oxford Univ., MPE, Califa team

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Advantages of IFS

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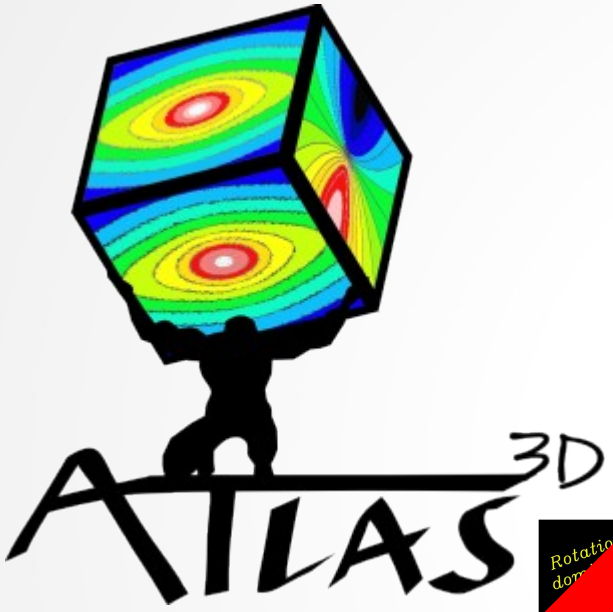
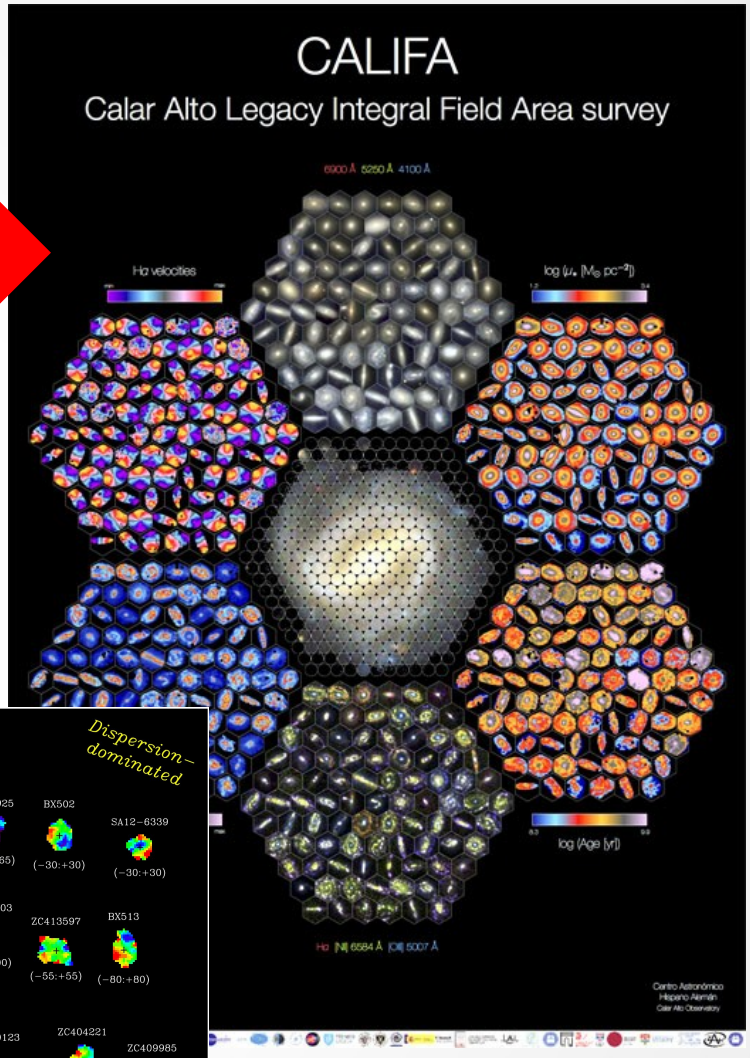
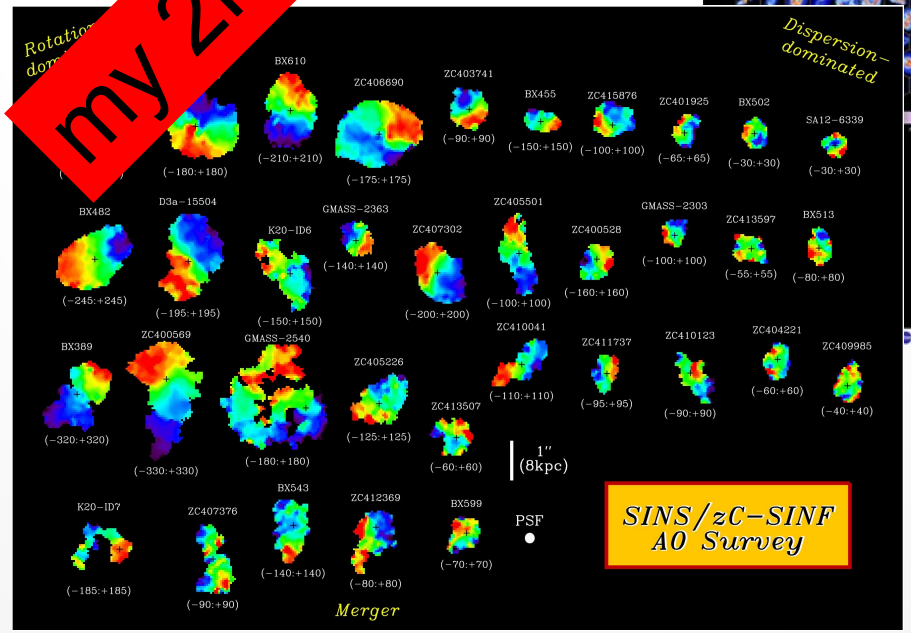


my 2nd talk + others





credit: Oxford Univ., MPE, Califa team

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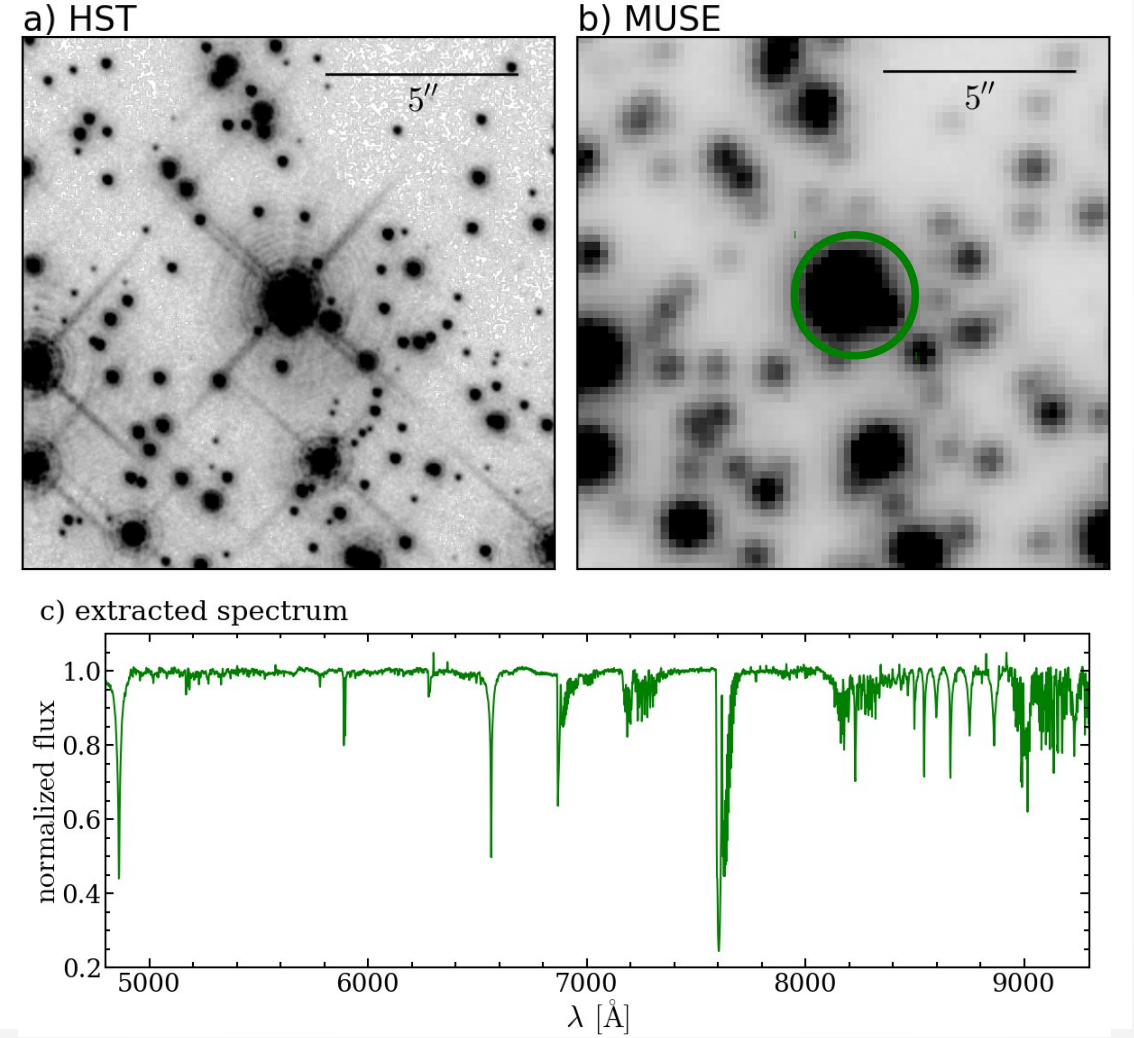
Advantages of IFS

- Deblend overlapping objects
  - e.g. central region in globular cluster NGC 6397



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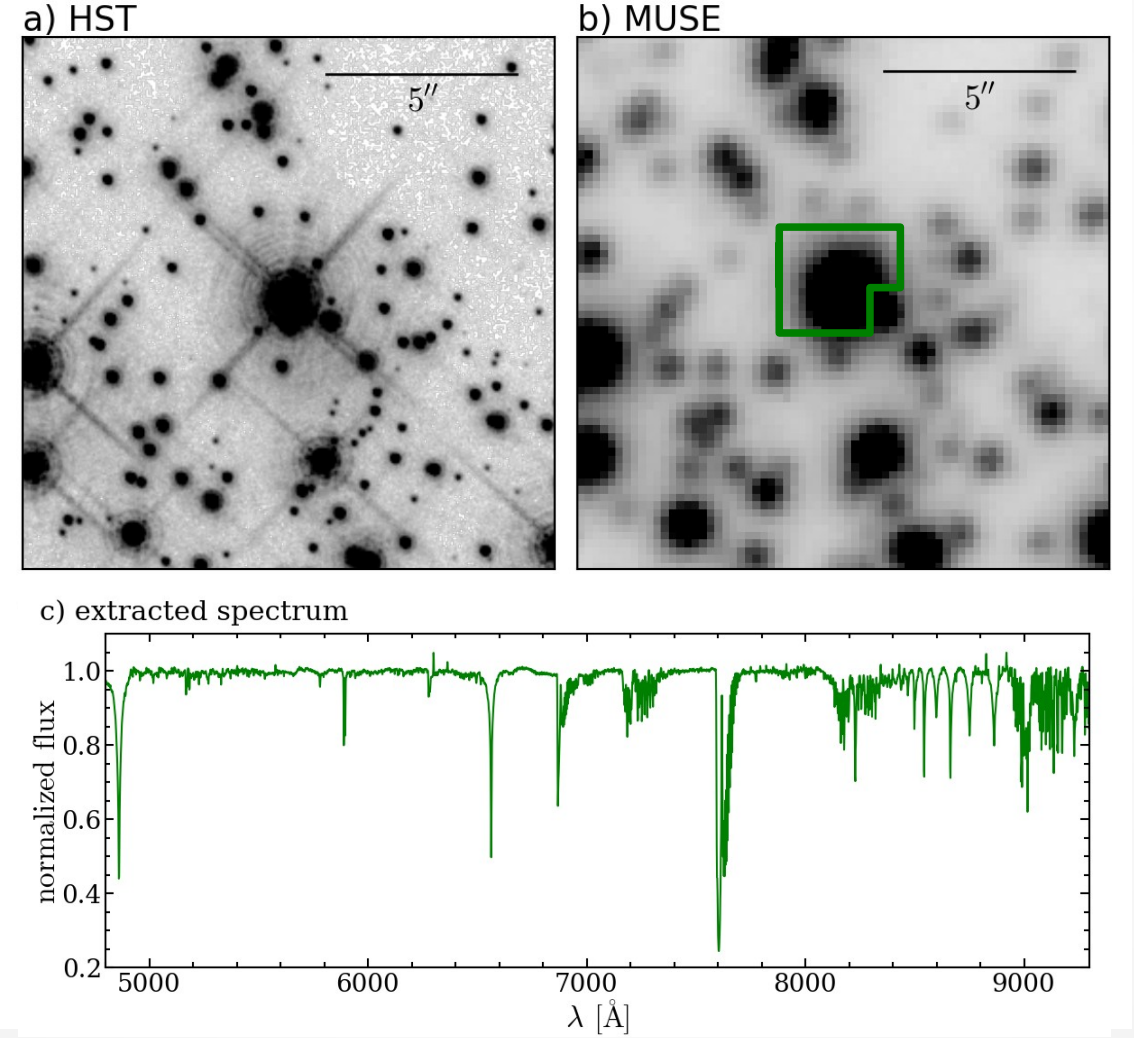

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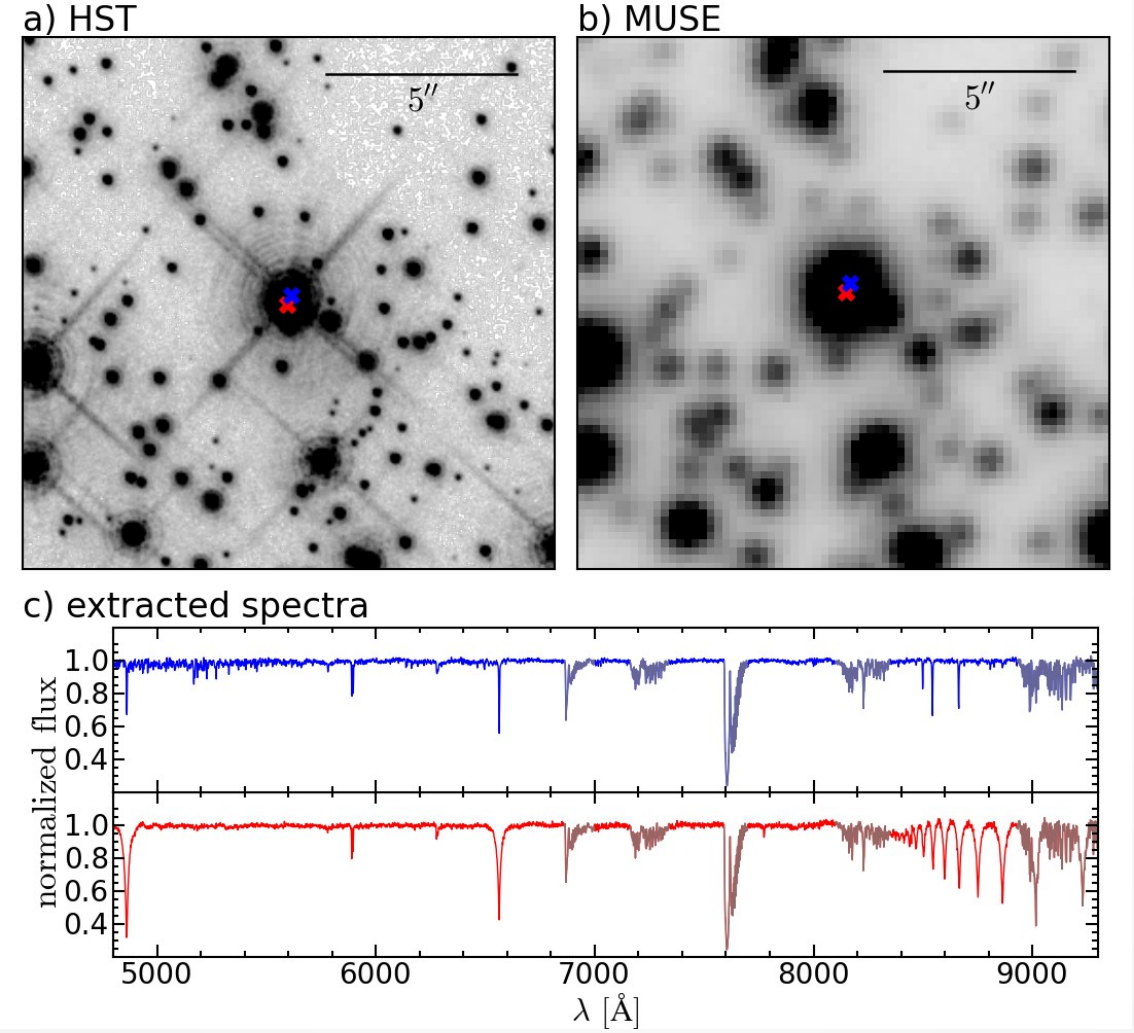
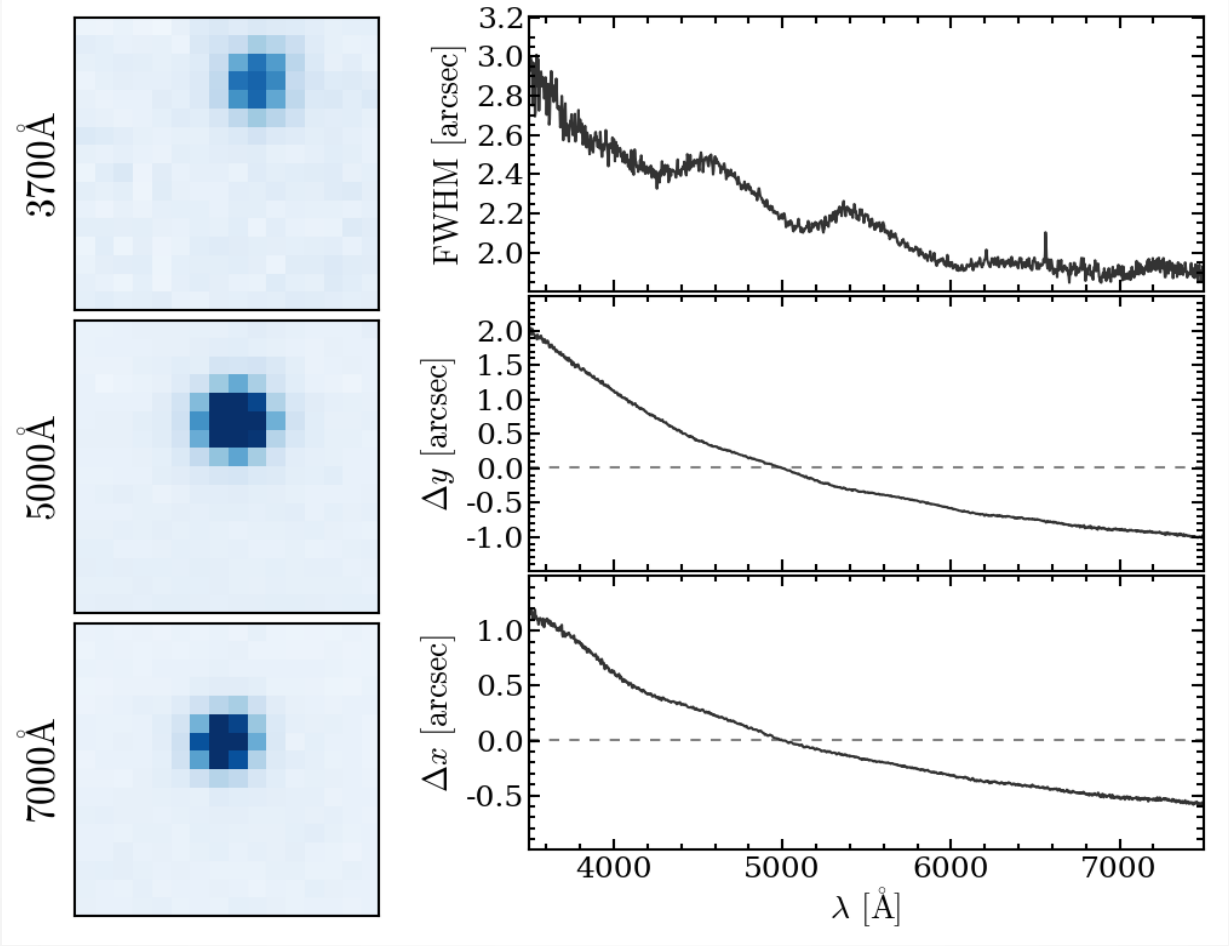


Advantages of IFS

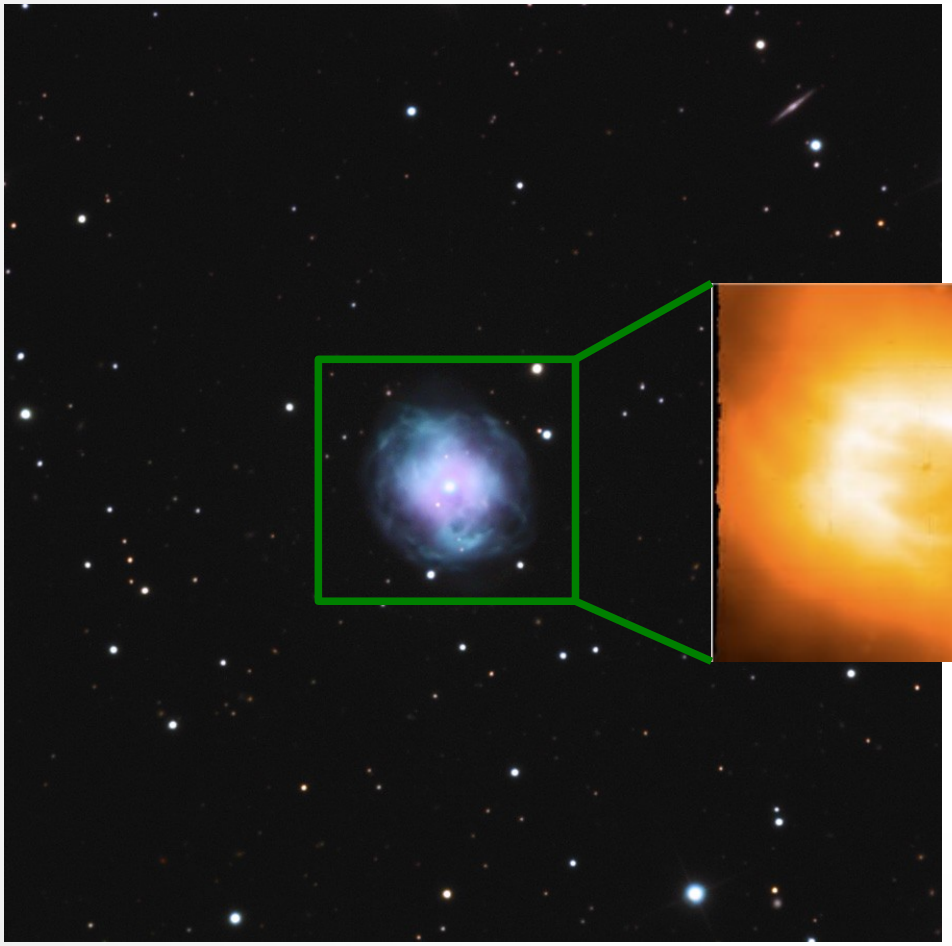
- Correct for atmospheric effects
  - e.g. observation of a standard star



Data provided by B.Husemann

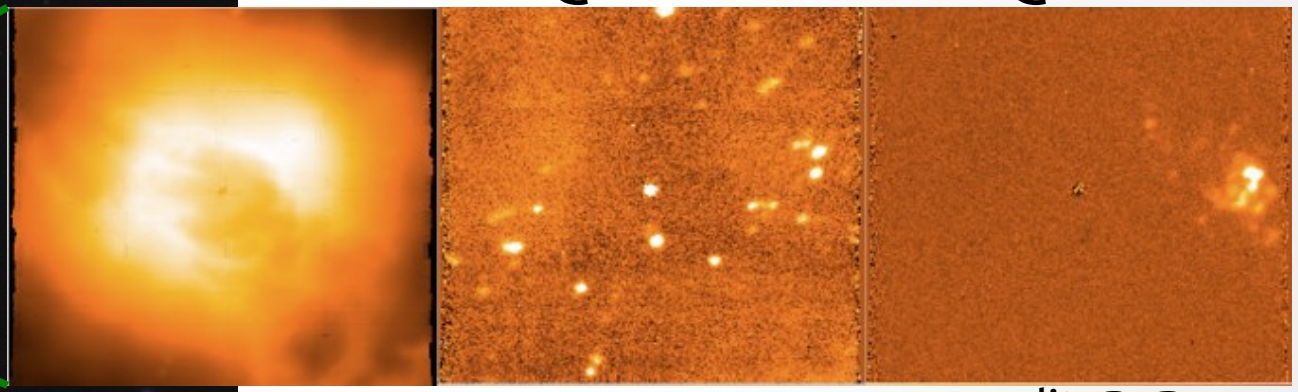
Advantages of IFS

- Looking behind the planetary nebula NGC 4631



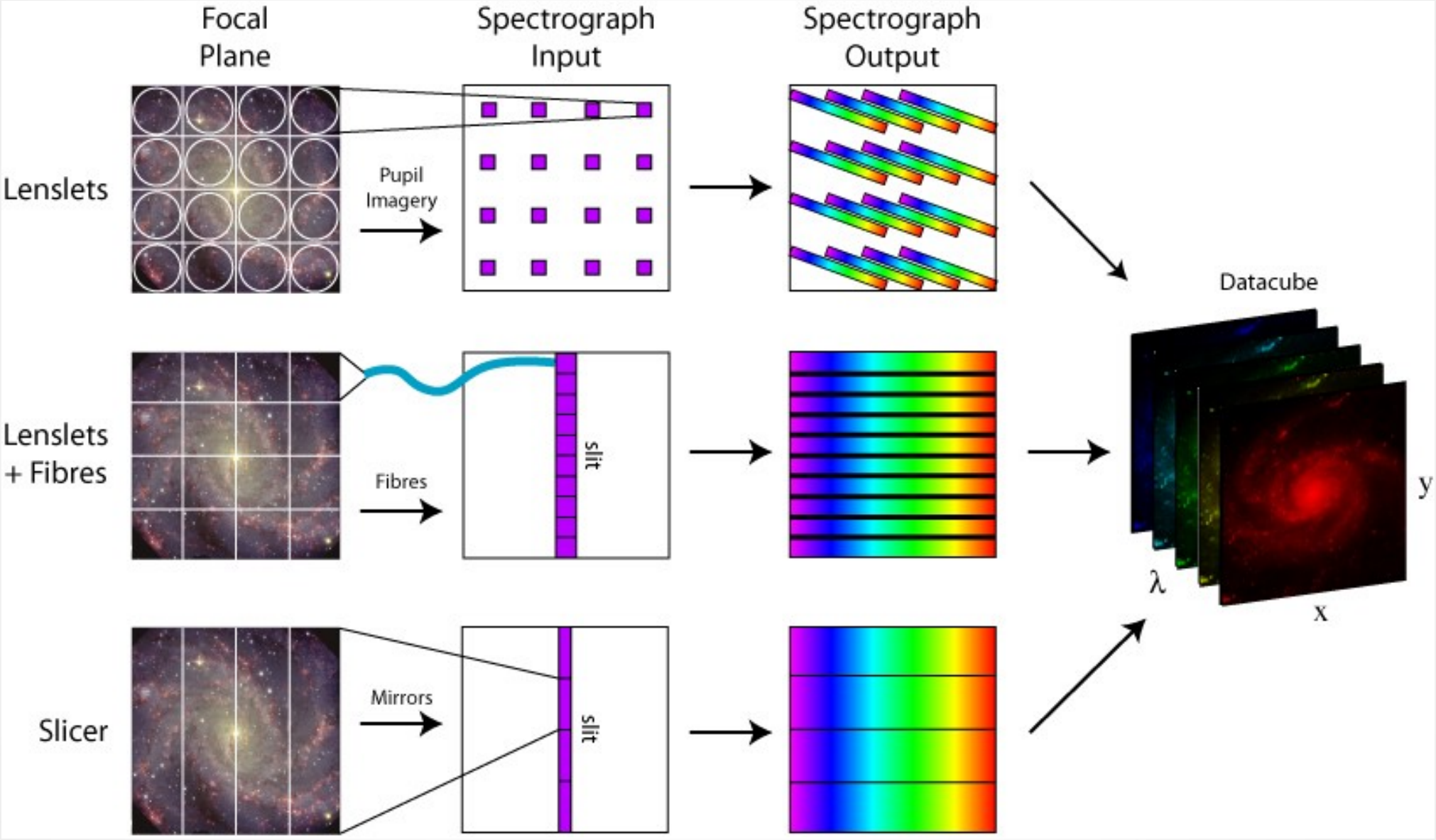
credit: Adam Block/Mount Lemmon SkyCenter/University of Arizona

Hα N@6584Å Hα@z=0.02



credit: R. Bacon

Instrument design



Credit: M. Westmoquette

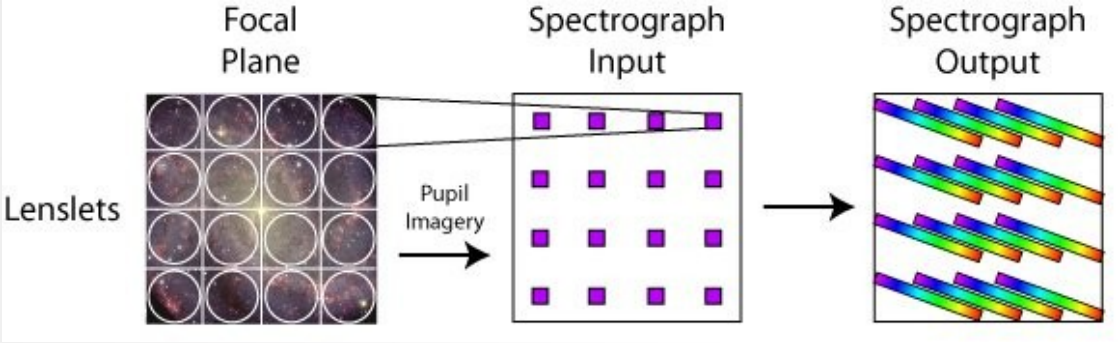
Apologies for my ignorance to...

- ...Fabry-Perot instruments
- ...Fourier-transform spectroscopy
- ...energy-resolving detectors

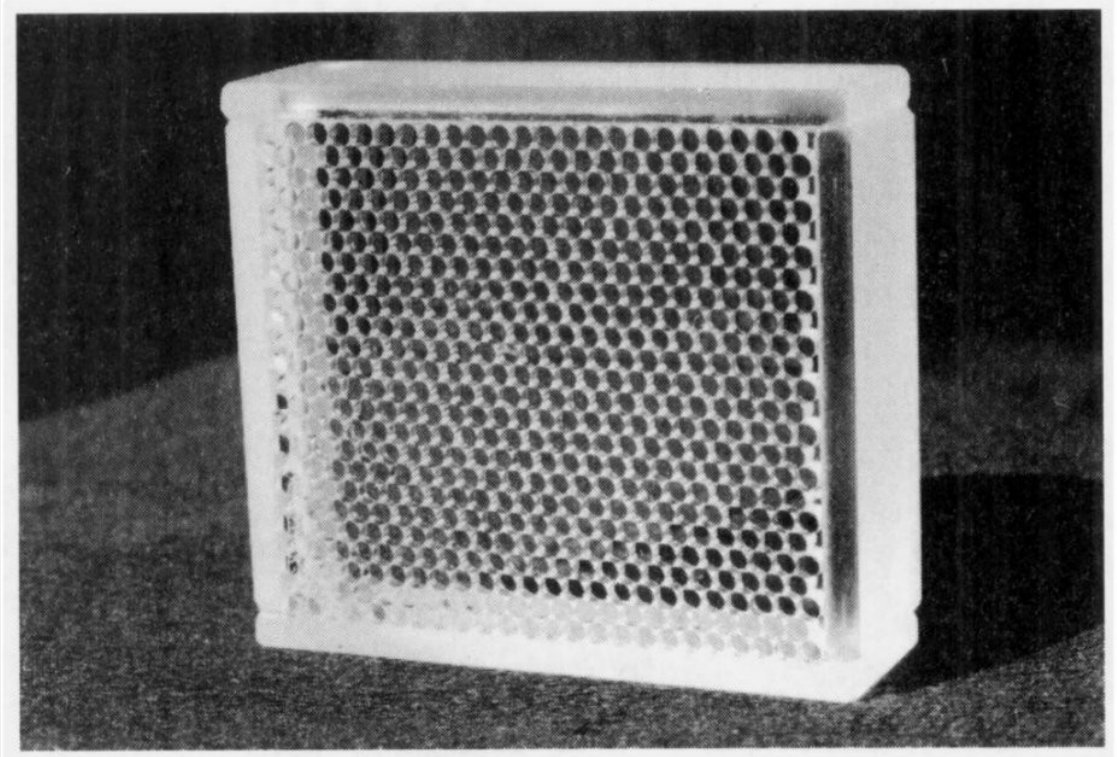
  → review by Eisenhauer & Raab (2015)

- ...ALMA
  - very different type of instrument
  - also delivers a datacube

Pure lenslet array



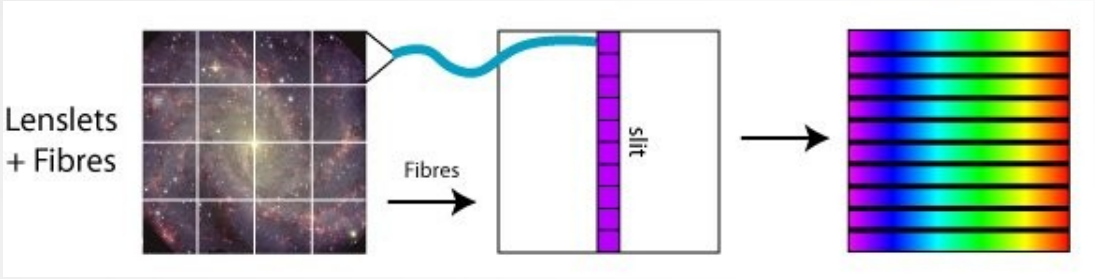
- Advantages:
  - simple
  - high throughput

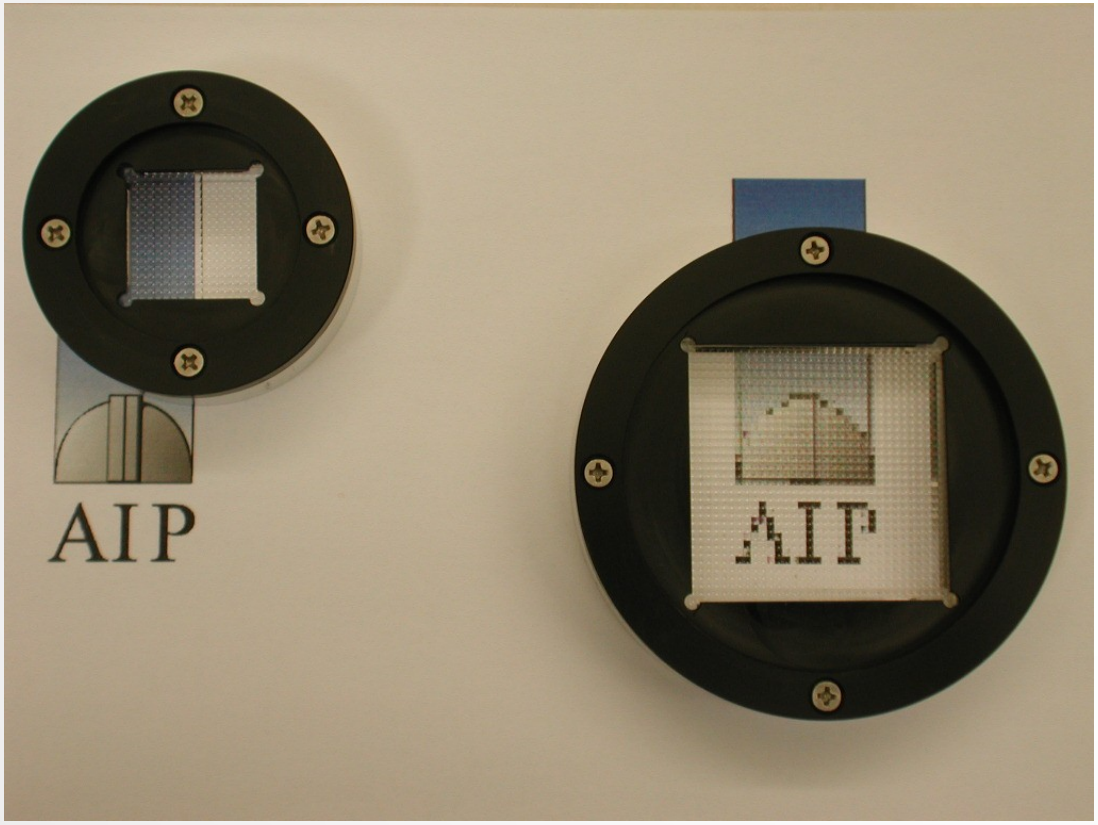


Tiger (Bacon et al. 1995)

- Disadvantages:
  - inefficient CCD usage
  - short wavelength range

Lenslets + fibres

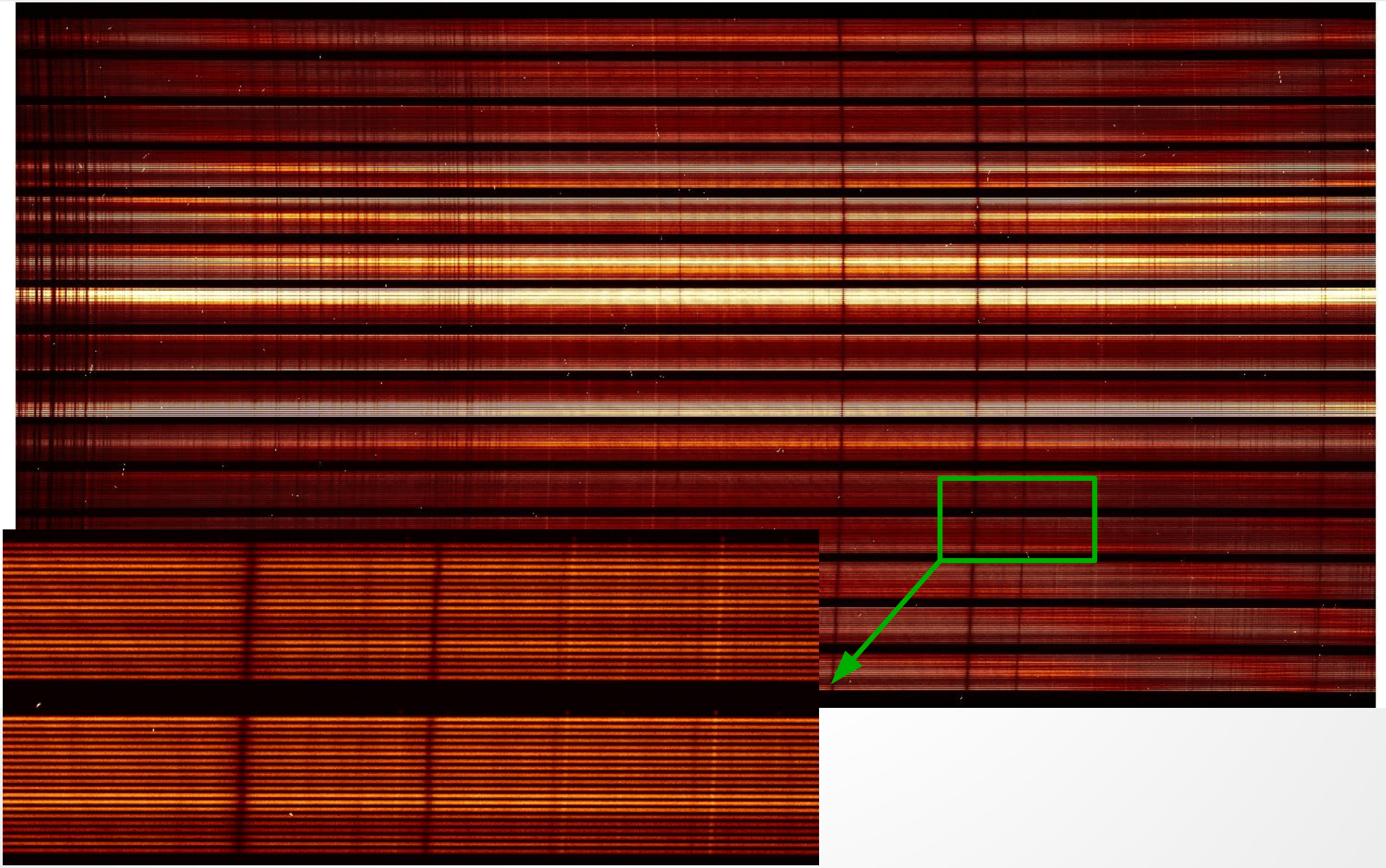




PMAS, credit: M. M. Roth

- Advantages
  - continuous FoV
  - piggyback to existing spectrograph
- Disadvantages
  - fibre effects (focal ratio degradation)
  - crosstalk on CCD

Raw data of ARGUS IFU

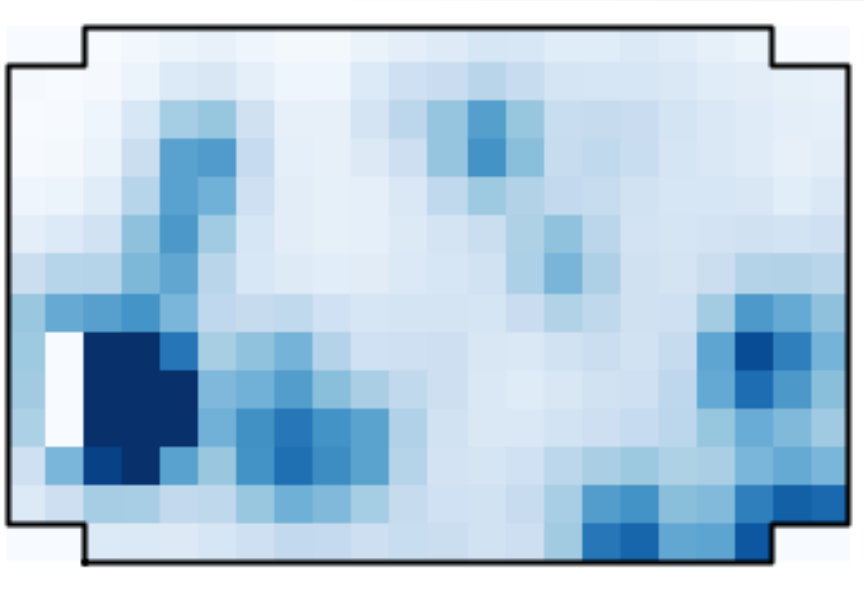


ARGUS

- integral field unit (IFU) of FLAMES
- 22x14 spaxels
- 0.3“/0.52“ sampling
- high spectral resolution (R<40000)

credit: ESO

- whitelight image of ARGUS data of 47Tuc



ARGUS

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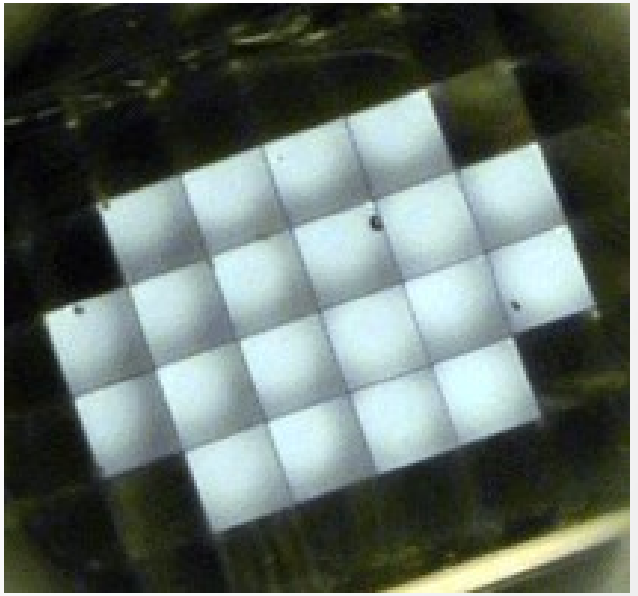
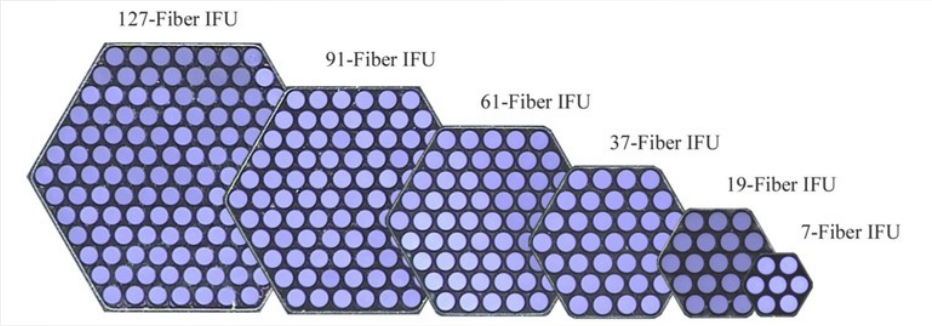
- also has a mode with deployable mini-IFUs

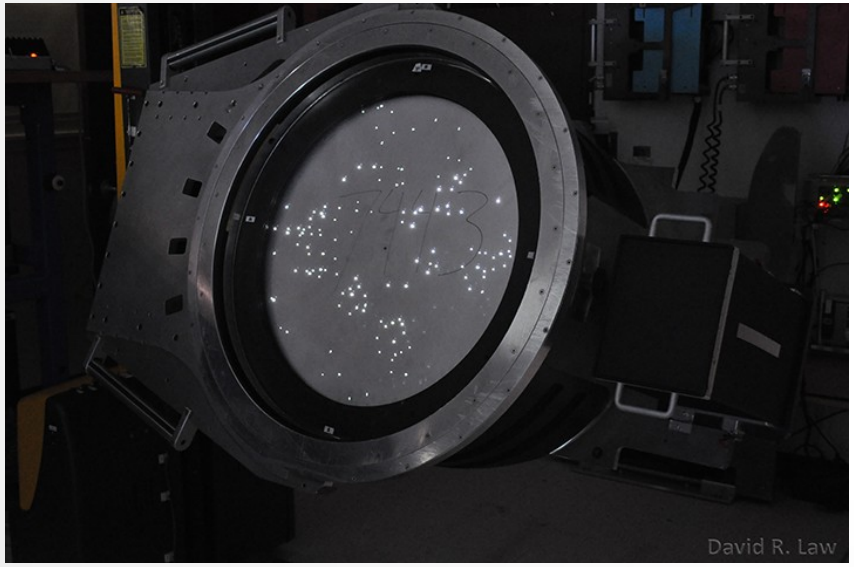


Galaxy survey IFUs



Drory et al. (2015)

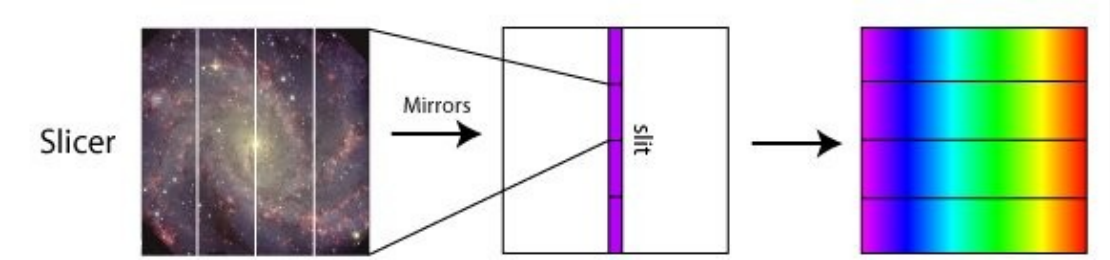
- pure fibre bundles
- high multiplex
- >1000 galaxies



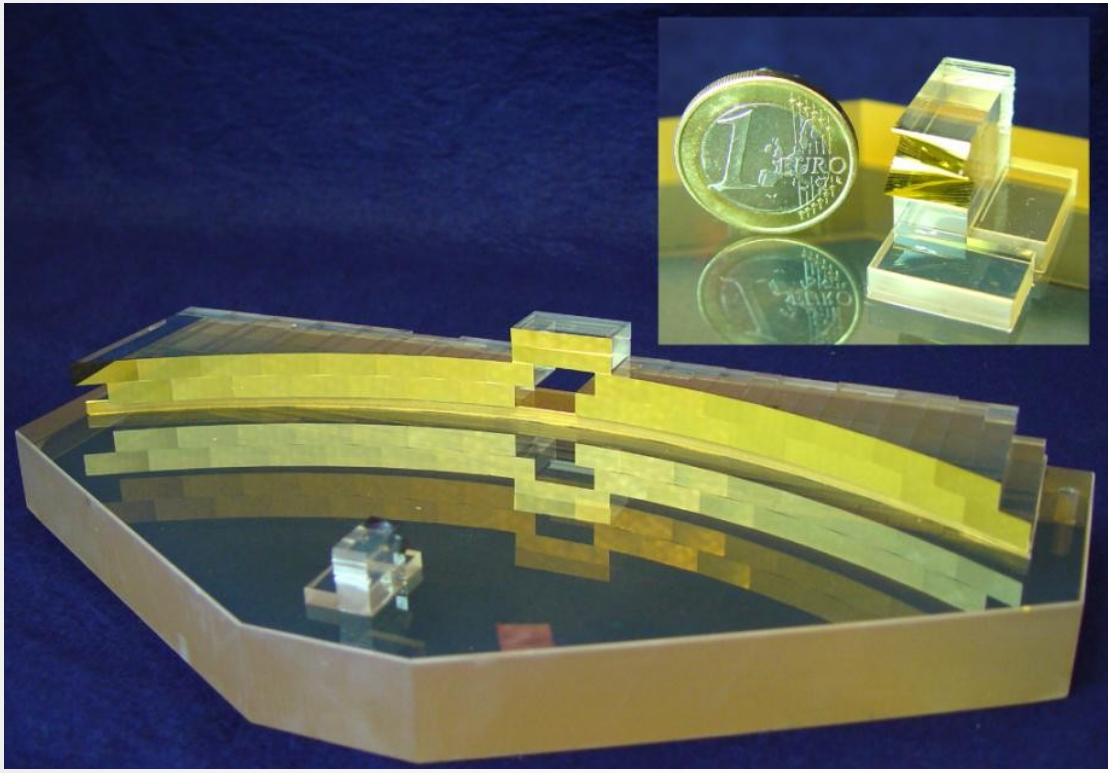
credit: D. R. Law

- MANGA (Bundy et al. 2015)
  - SDSS telescope
- SAMI (Croom et al. 2012)
  - AAOmega spectrograph
  - successor already planed

Slicer



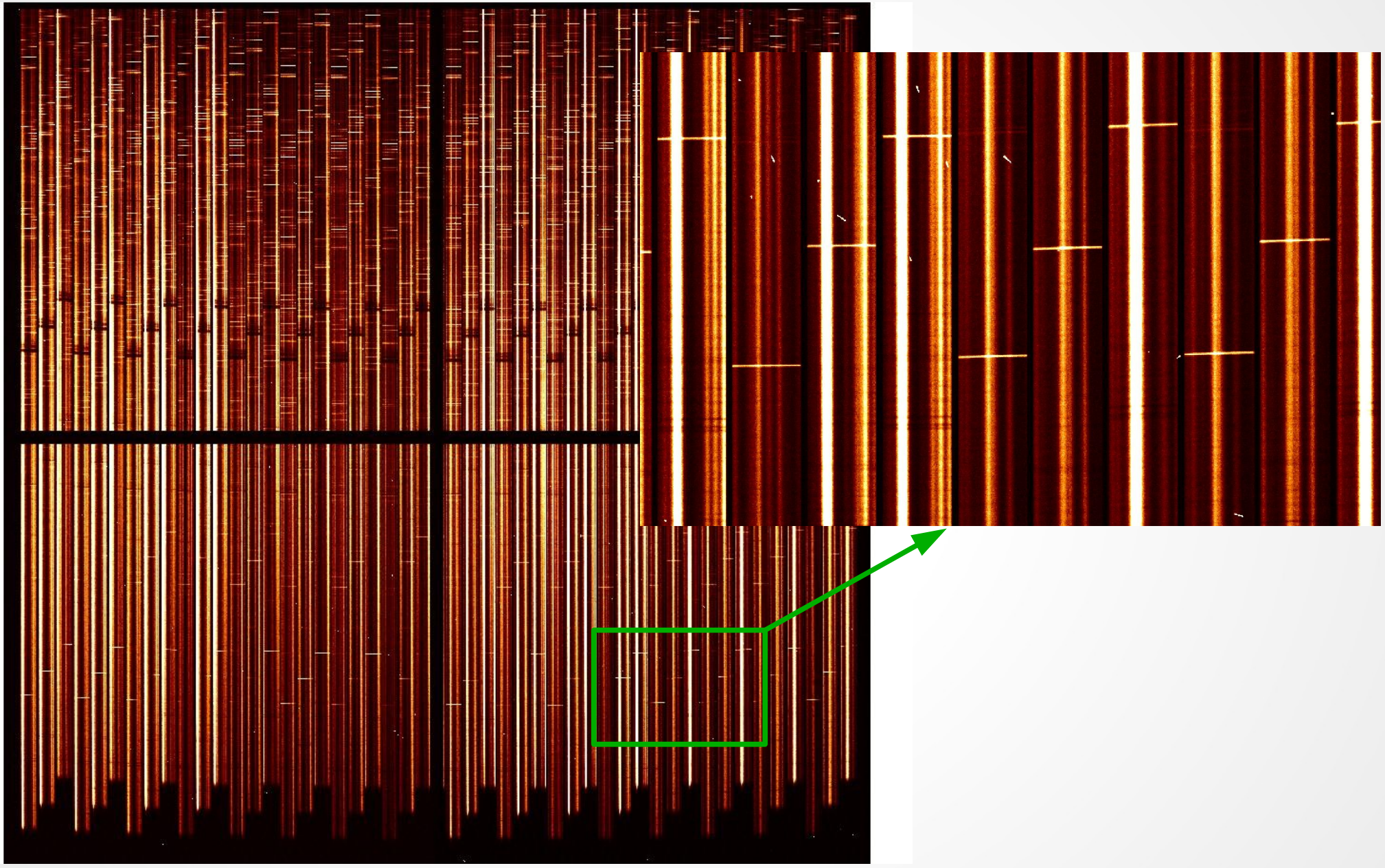
- oldest IFU concept (Bowen 1938)



SINFONI slicer unit, credit: ESO

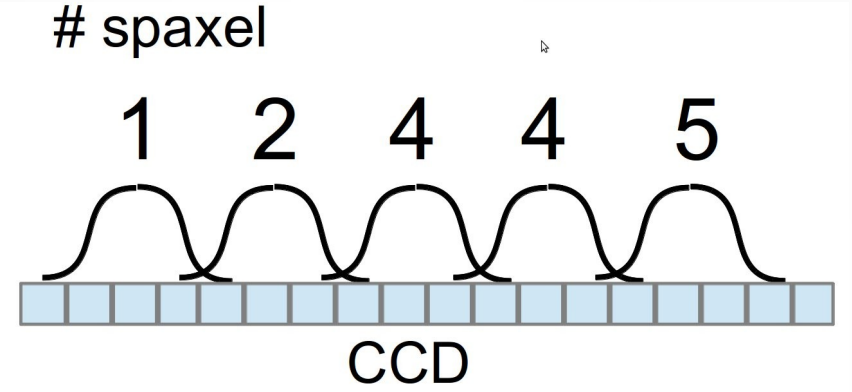
- Advantages
  - high throughput
  - most efficient CCD usage
- Disadvantages
  - optics challenging to manufacture

Raw data of an image slicer

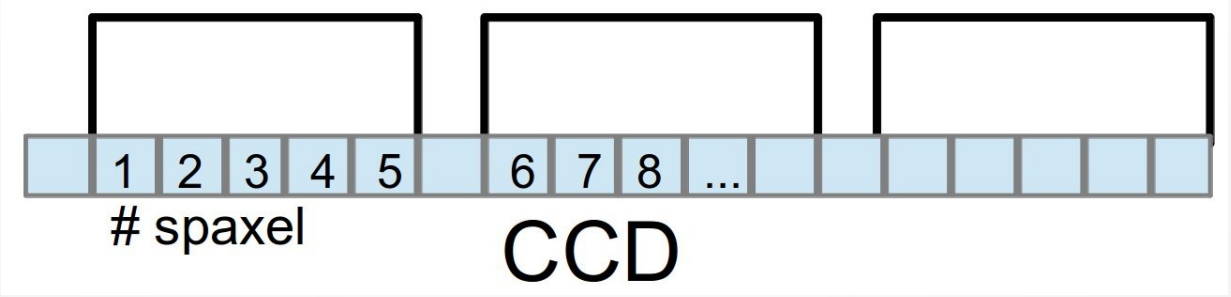


Creating the spatial grid

- Fibres
  - spatial sampling defined in focal plane



- Slicer
  - spatial sampling along 1st axis at slicer
  - spatial sampling along 2nd axis at CCD



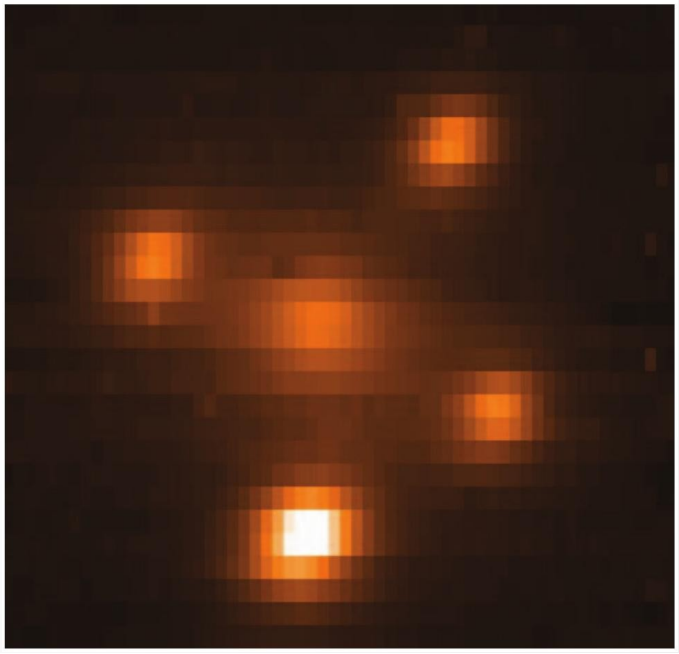
SINFONI

- AO-supported
- infrared (J, H, K)
- R ~ 2000 – 4000
- sampling on sky:

Field of view	Spaxel size on the sky
$8'' \times 8''$	125mas×250mas
$3'' \times 3''$	50mas×100mas
$0.8'' \times 0.8''$	12.5mas×25mas

- probably most successful IFS worldwide (->2nd talk)

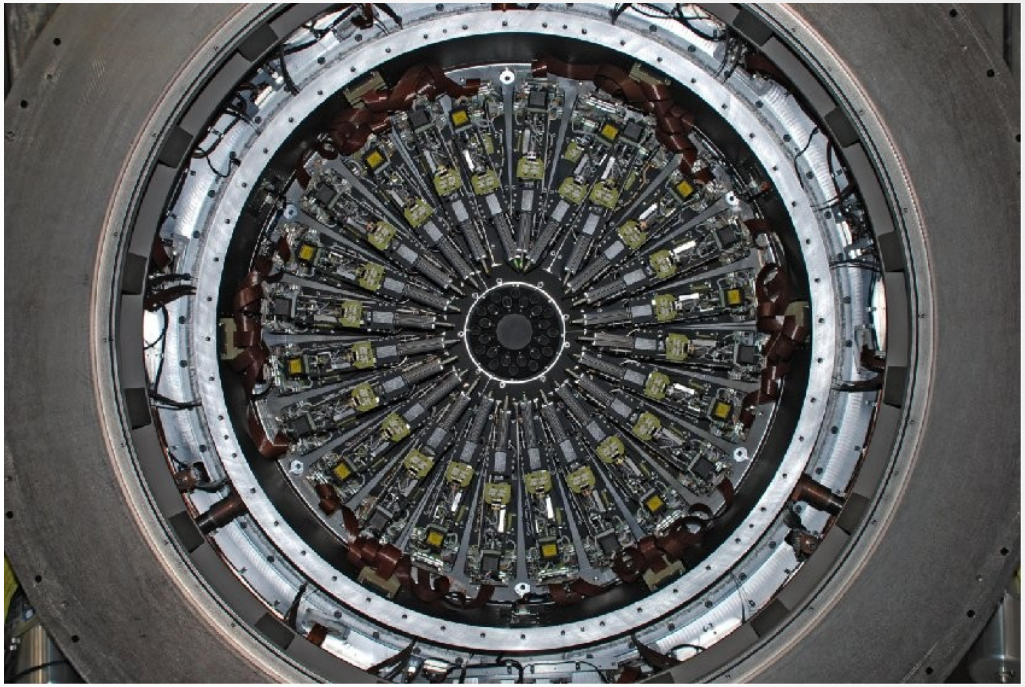
credit: ESO

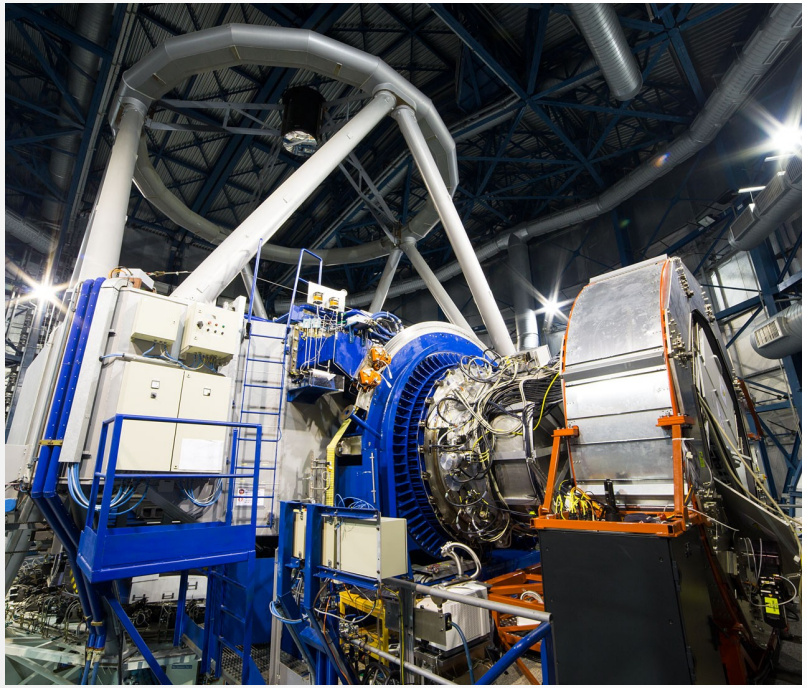


Einstein cross (Bonnet et al. 2004)

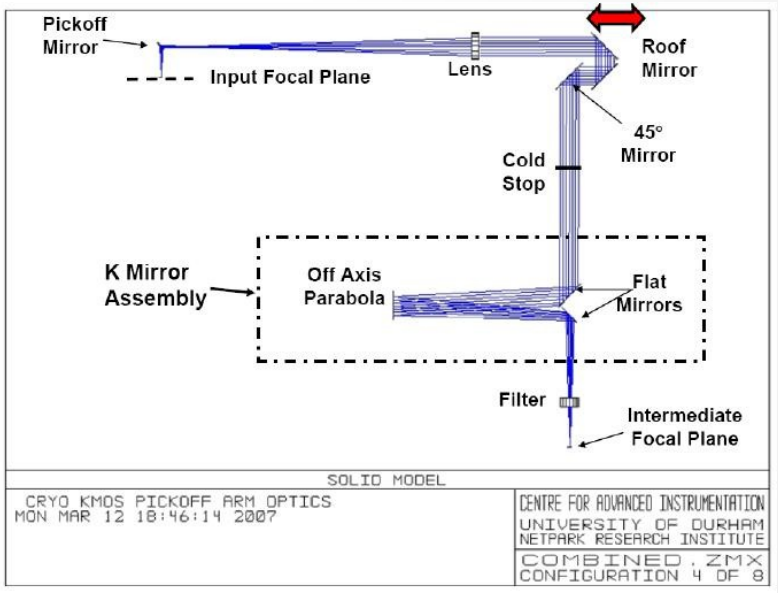
KMOS

- 24 deployable IFUs
- each: 14x14 spaxels, 0.2“ sampling
- infrared, R~3500



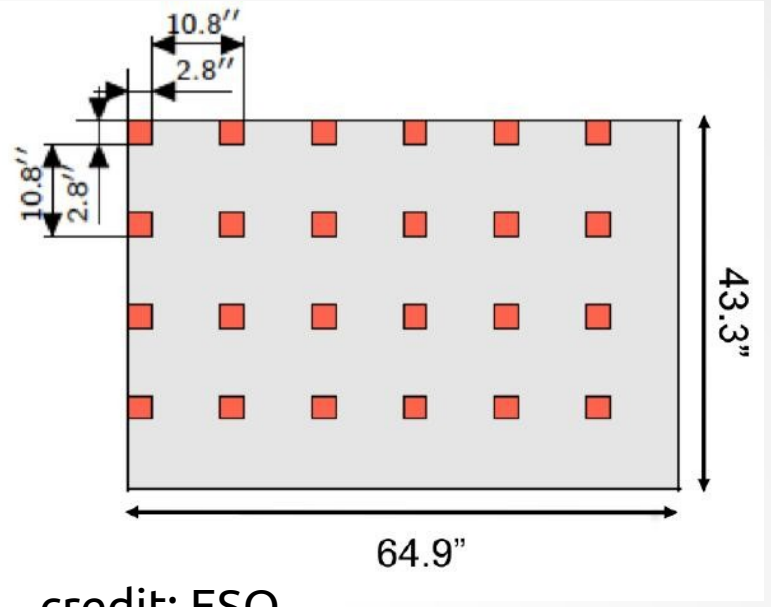


credit: ESO

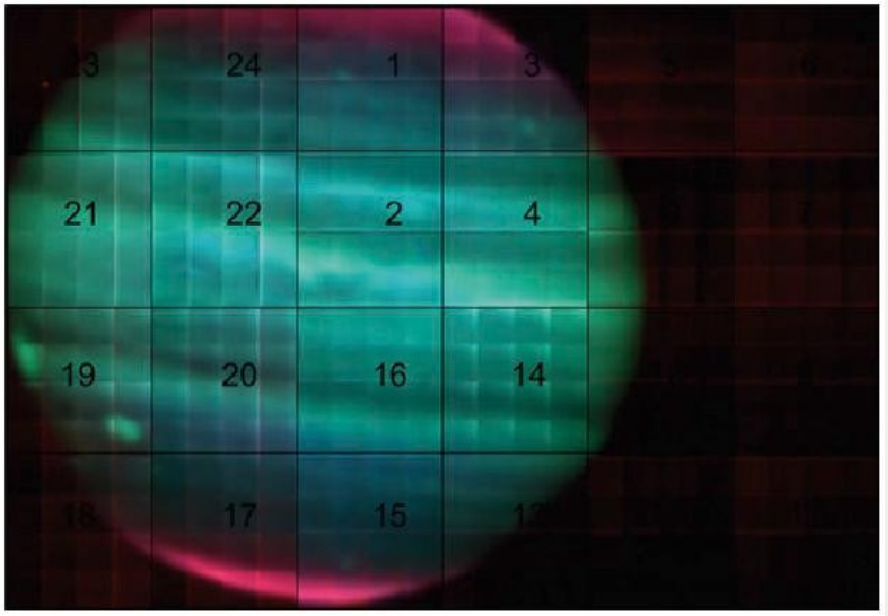


KMOS mosaic mode

- possibility to get continuous FoV
  - about 1 arcmin²
  - 16 offsets required
- Jupiter observation:
- good astrometry is challenging



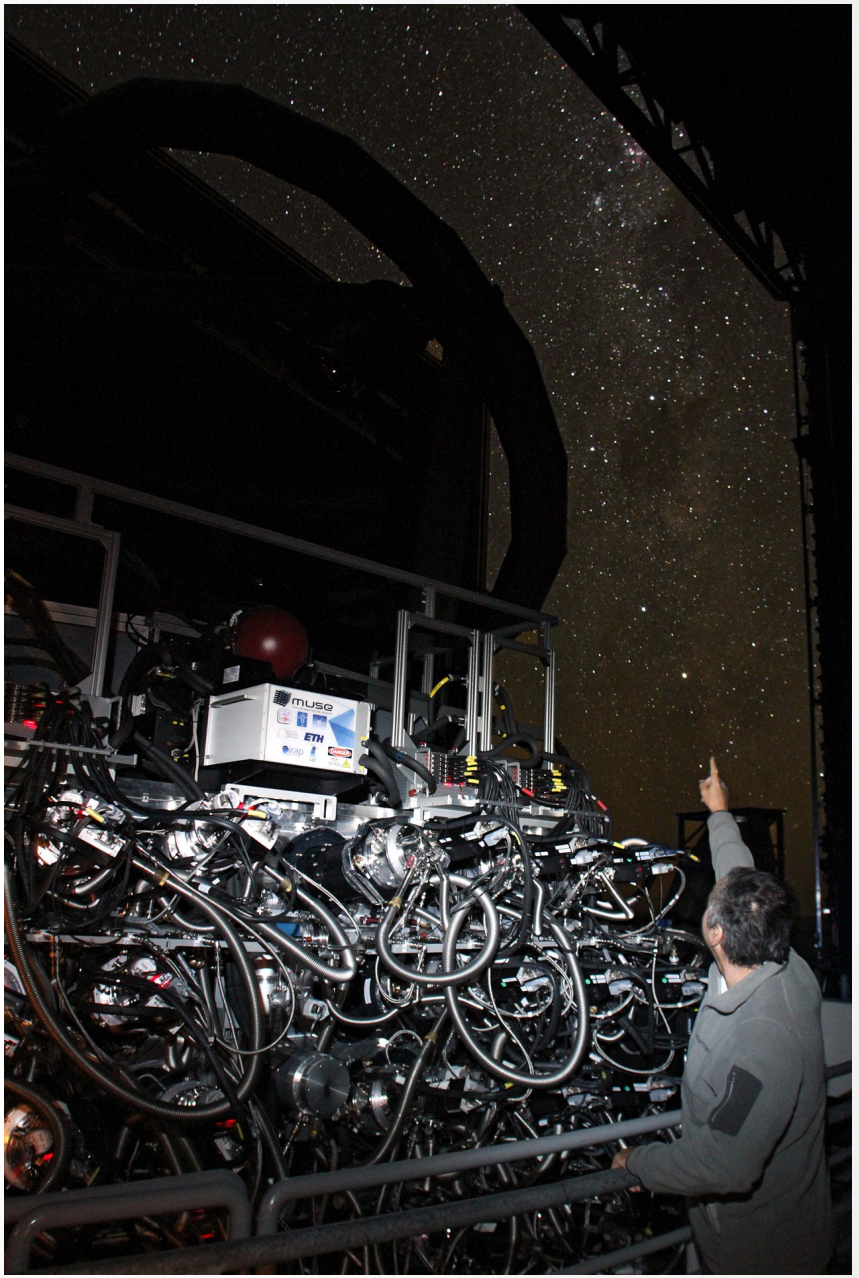
credit: ESO



Sharples et al. (2013)

MUSE

- panoramic IFS
  - combines 24 IFU
  - 1'x1' FoV
  - 0.2'' sampling
- long wavelength range
  - 480 – 930 nm
  - R ~ 1700 – 3500
- very stable
- very high troughput
- AO will come soon!



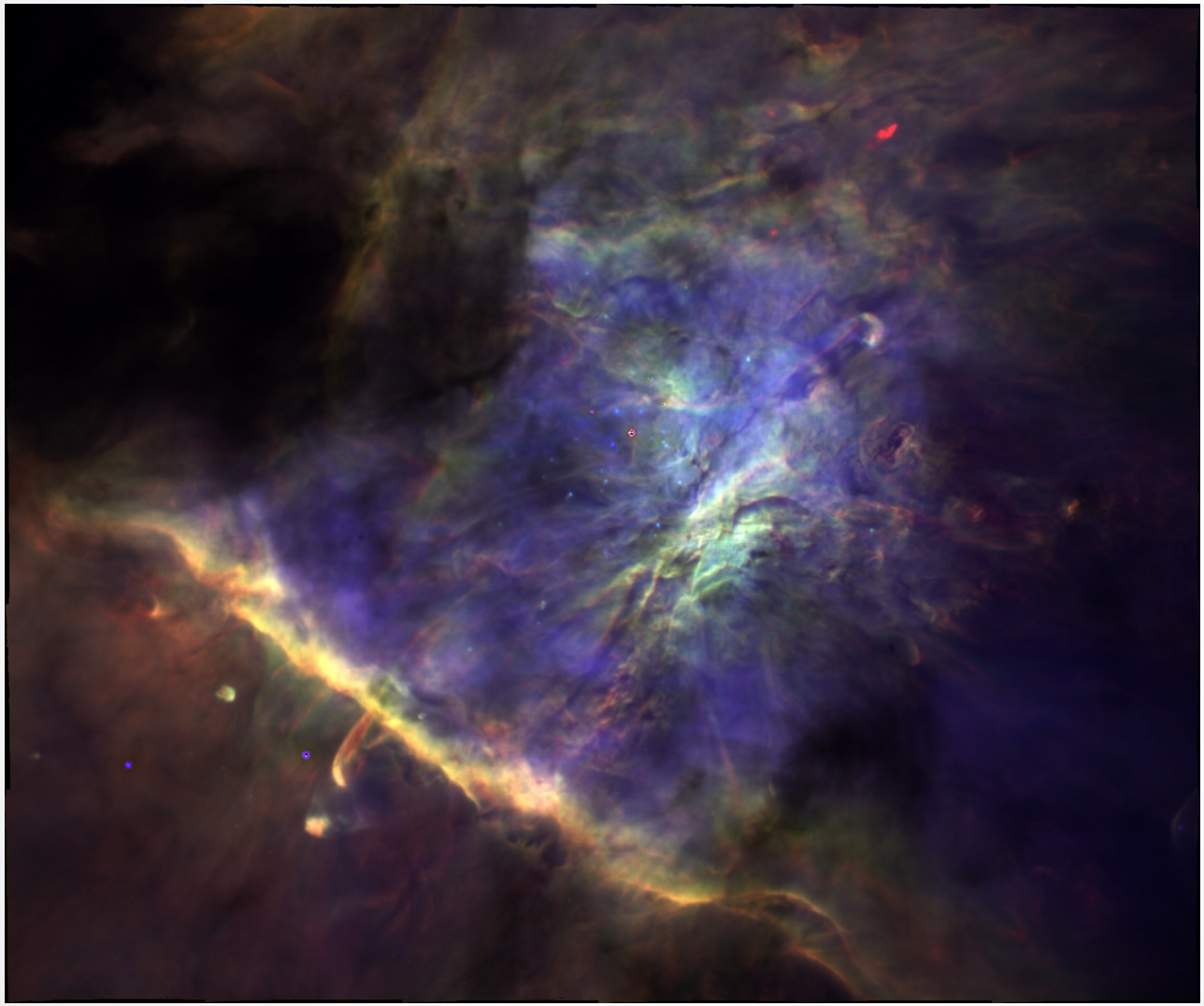
credit: ESO

A journey through MUSE

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

Some impressions

- Orion nebula (Weilbacher et al. 2015)
  - http://muse-vlt.eu/science/m42/



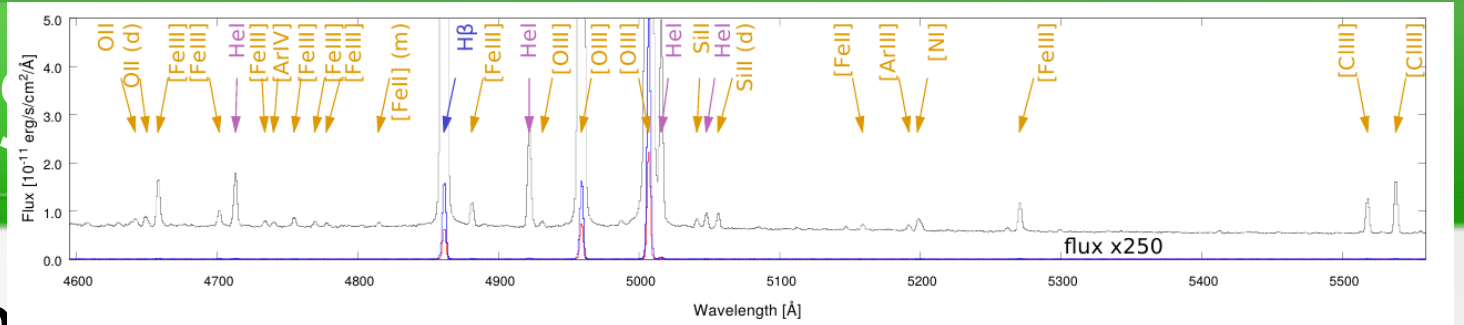
blue – Hß

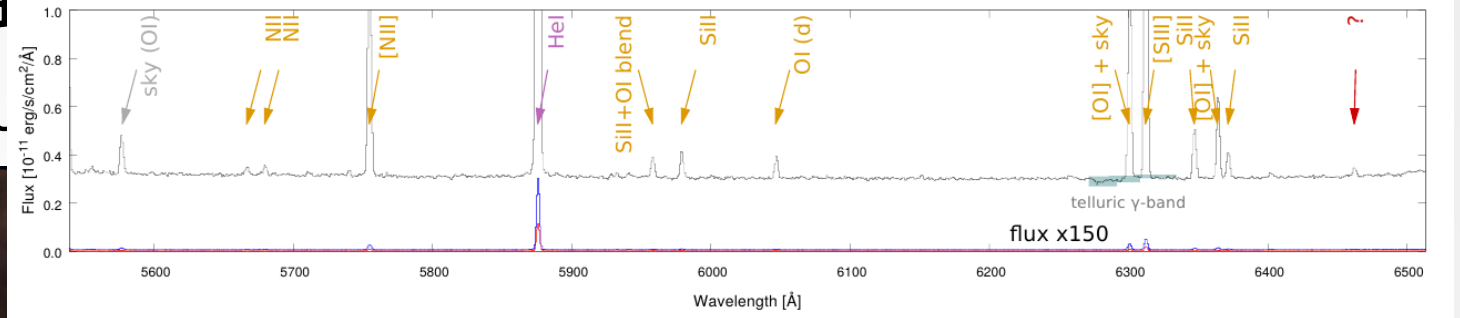
green – [NII]

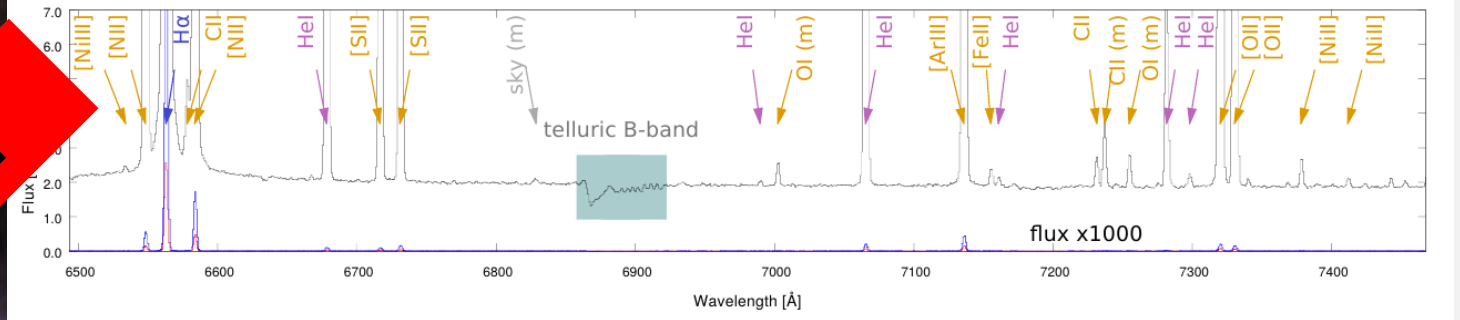
red – [SII]

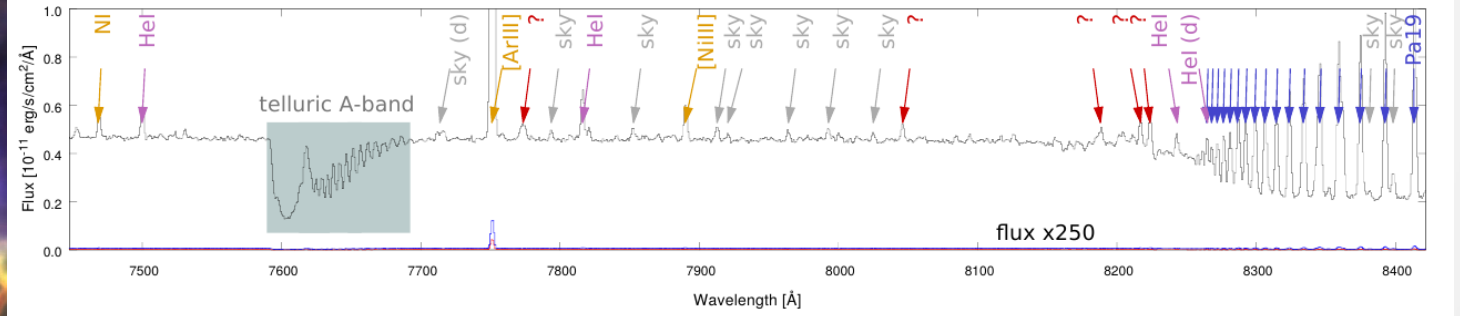
- Orion nebula
  - http://mu

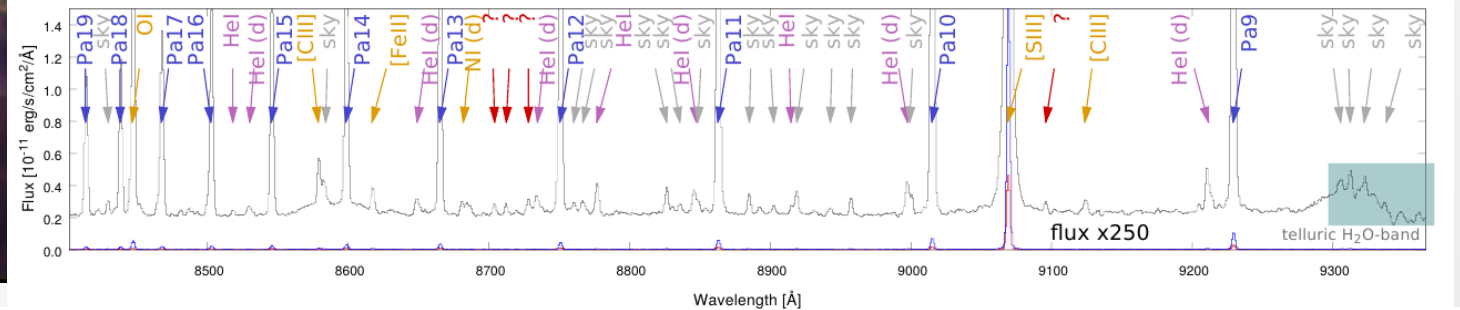
1 million spectra!





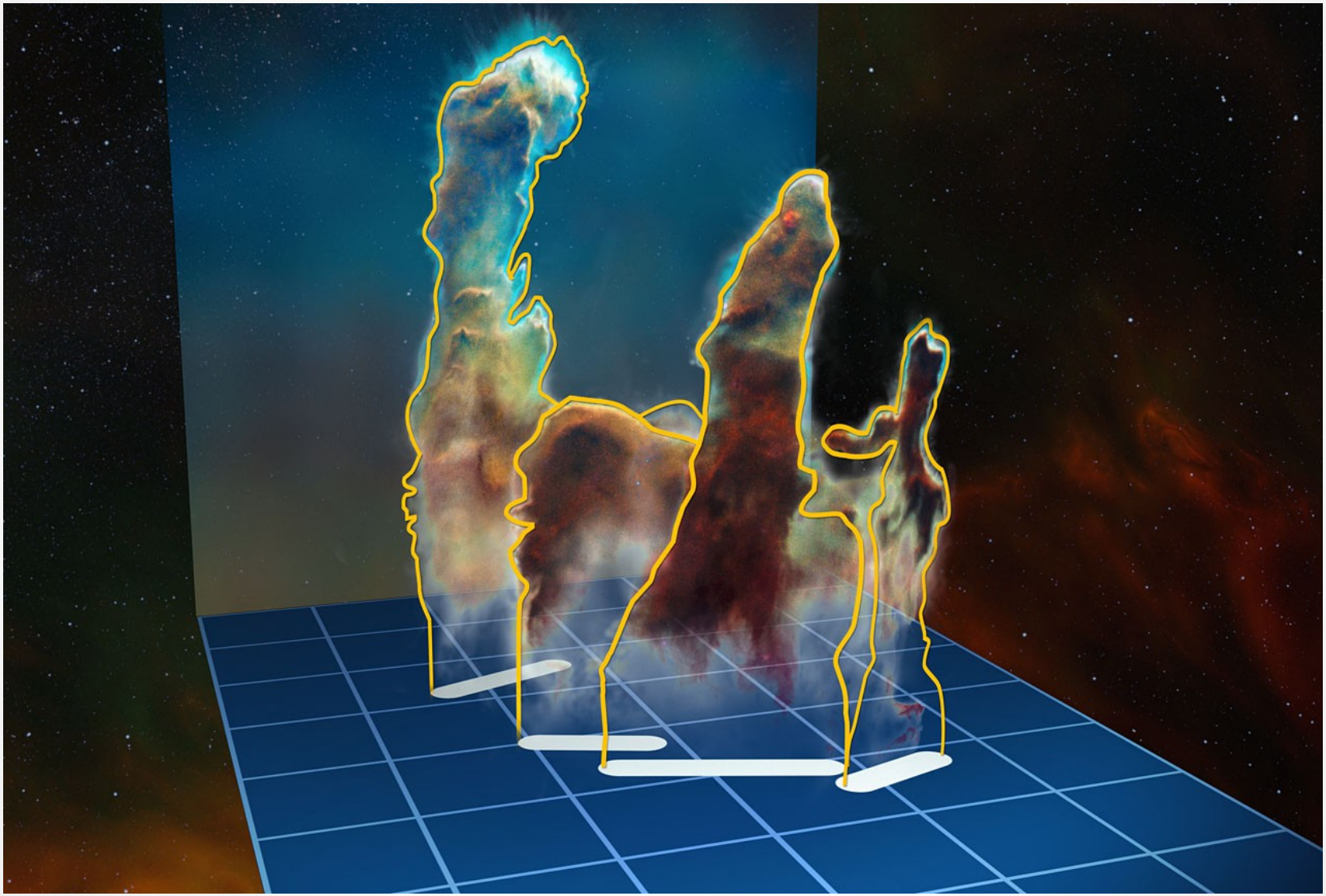






Some impressions

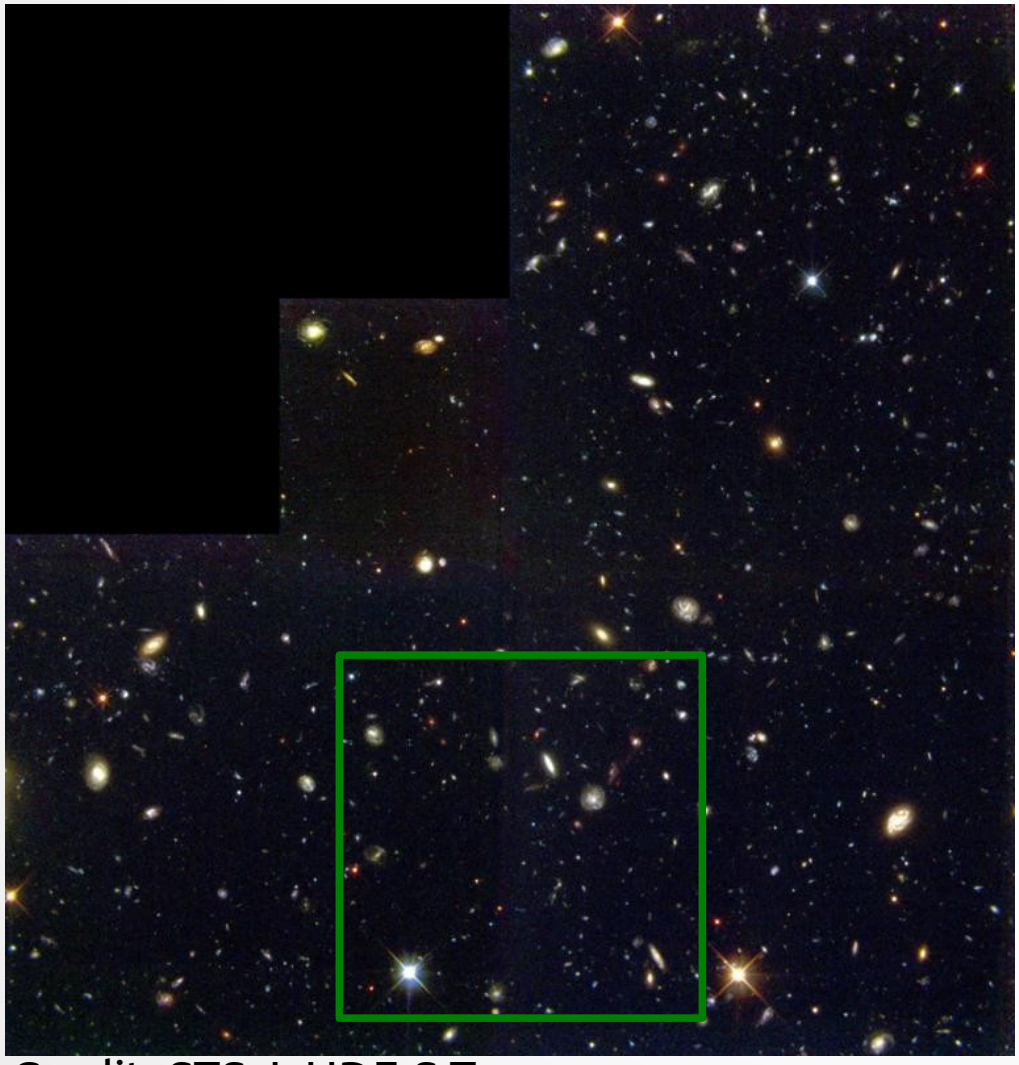
- The Pillars of Creation in 3D (McLeod et al. 2015)



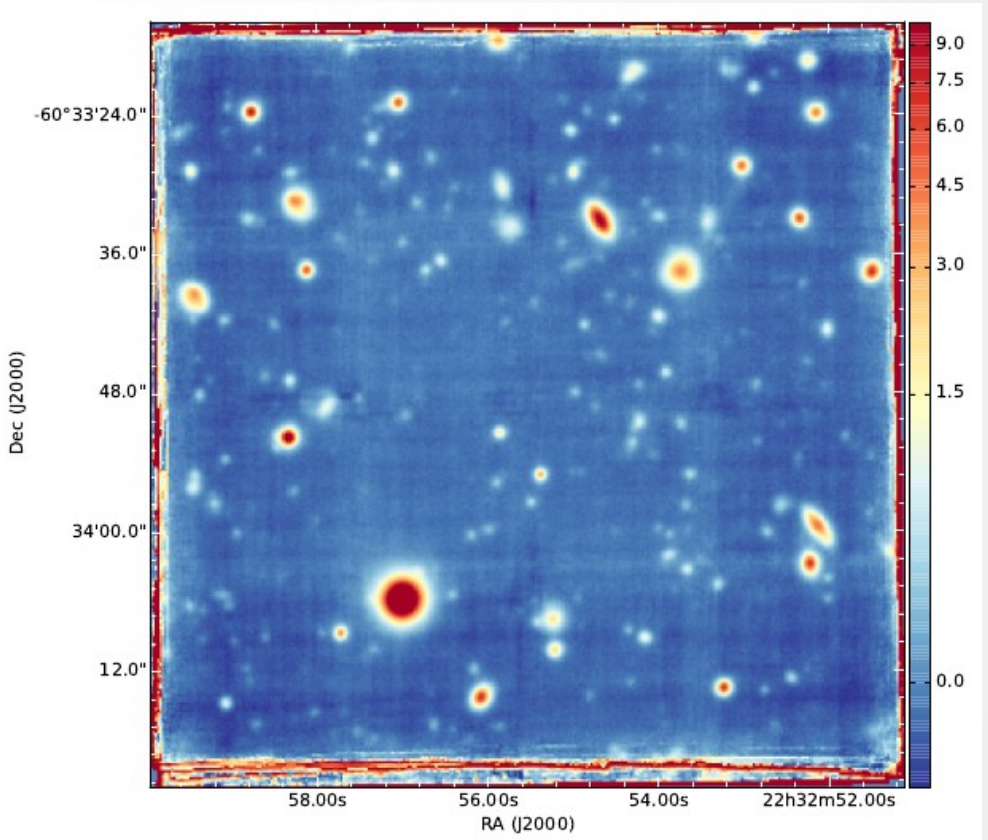
Credit: ESO

Some impressions

- Hubble deep field (Bacon et al. 2015)
  - http://muse-vlt.eu/science/hdfs-v1-0/



Credit: STScI, HDF-S Team



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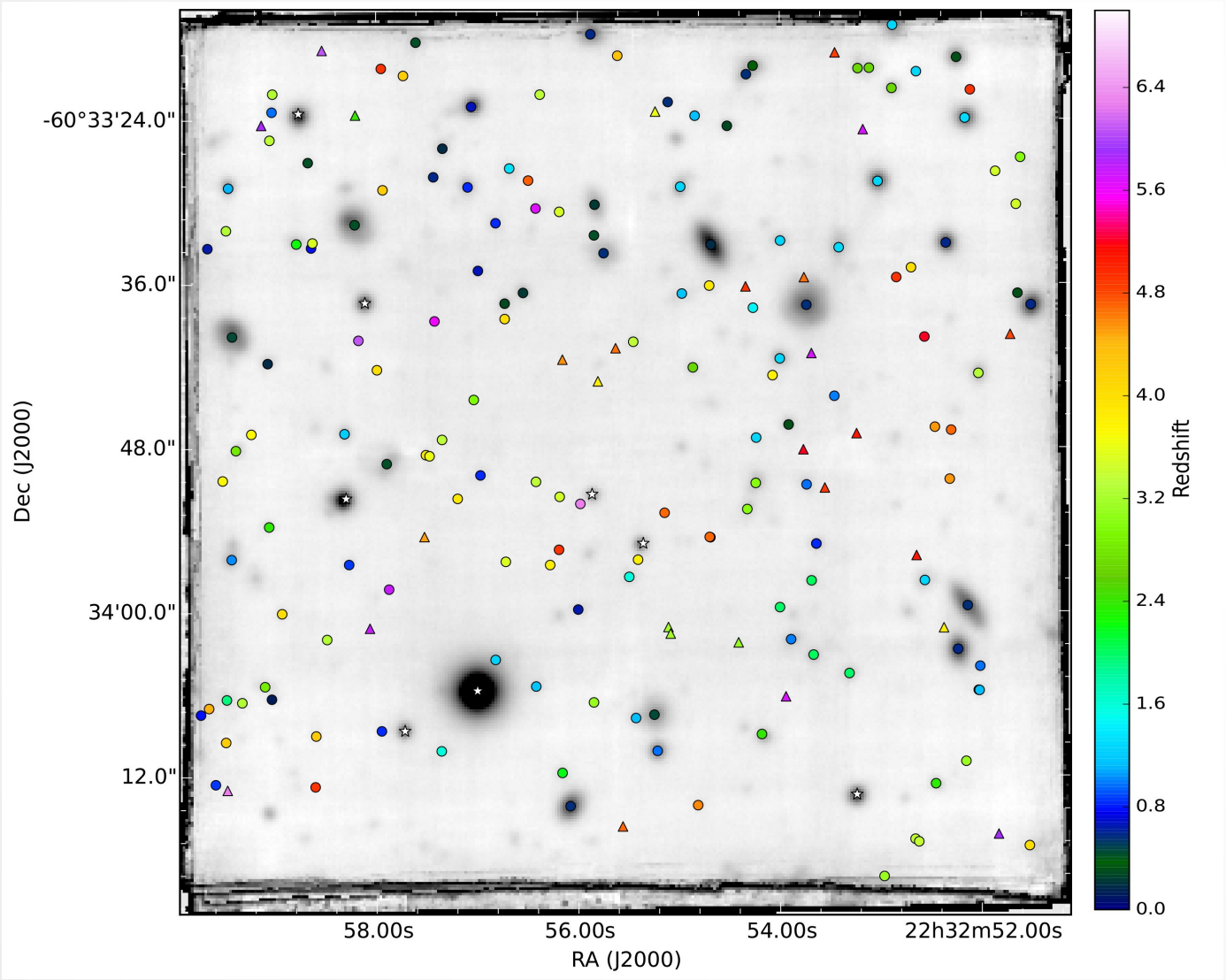


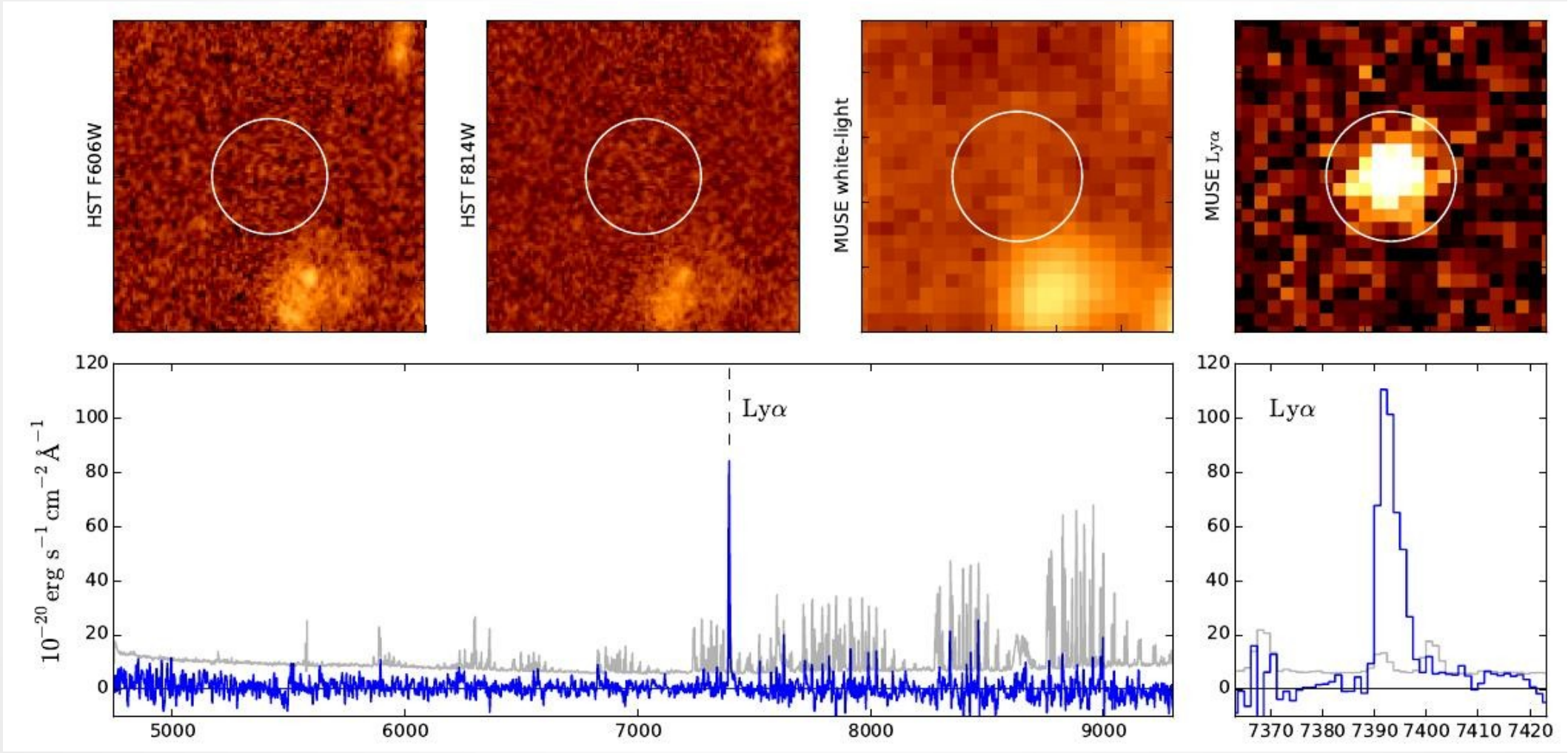
circles: HST detections

triangles: new sources

26 new detetcions in one of the deepest Hubble fields

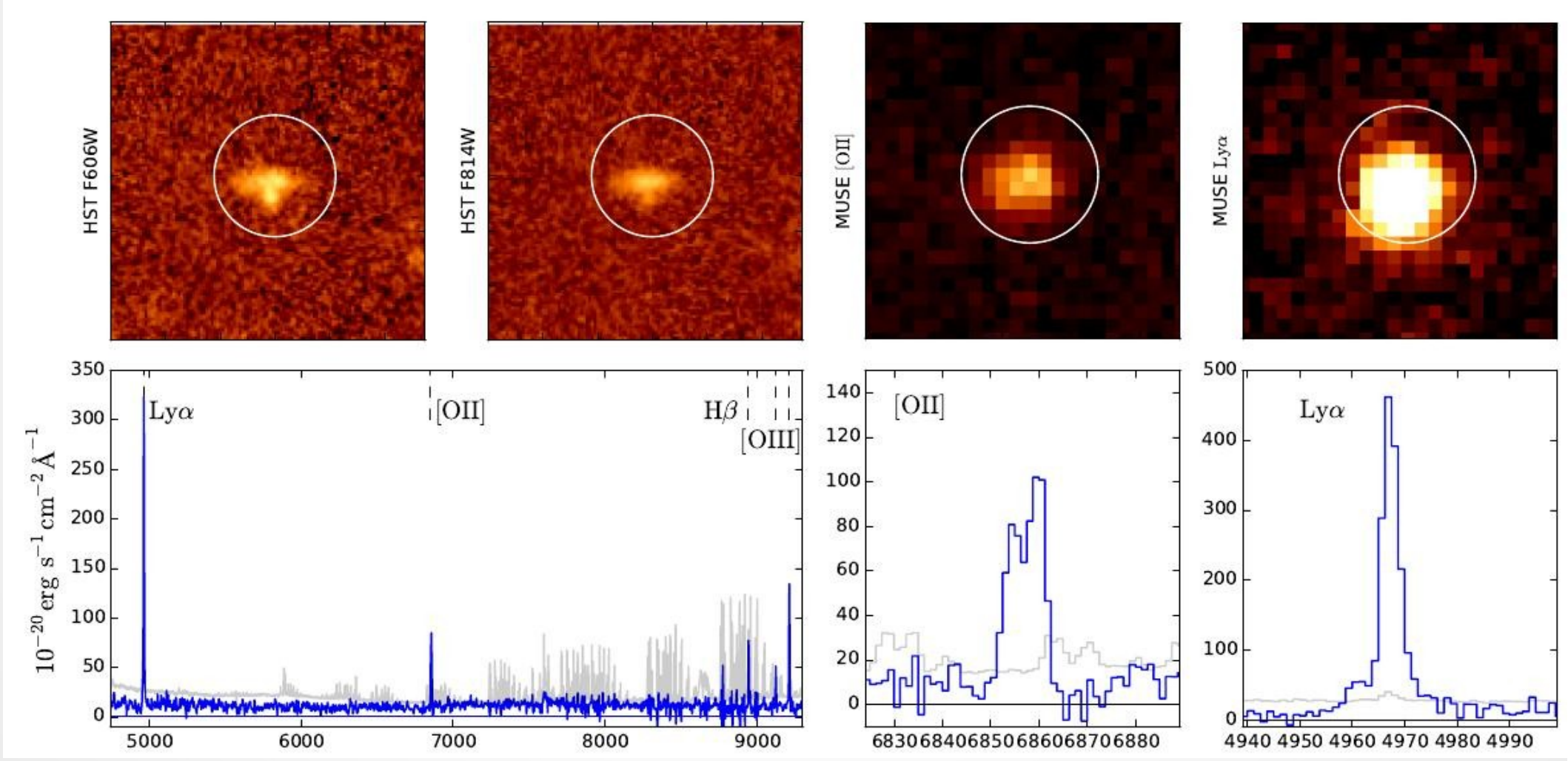
Some impressions

- Hubble deep field (Bacon et al. 2015)
  - example of newly detected source



Some impressions

- Hubble deep field (Bacon et al. 2015)
  - example of blended sources



Some impressions

- The Sombrero galaxy (courtesy of E. Emsellem)

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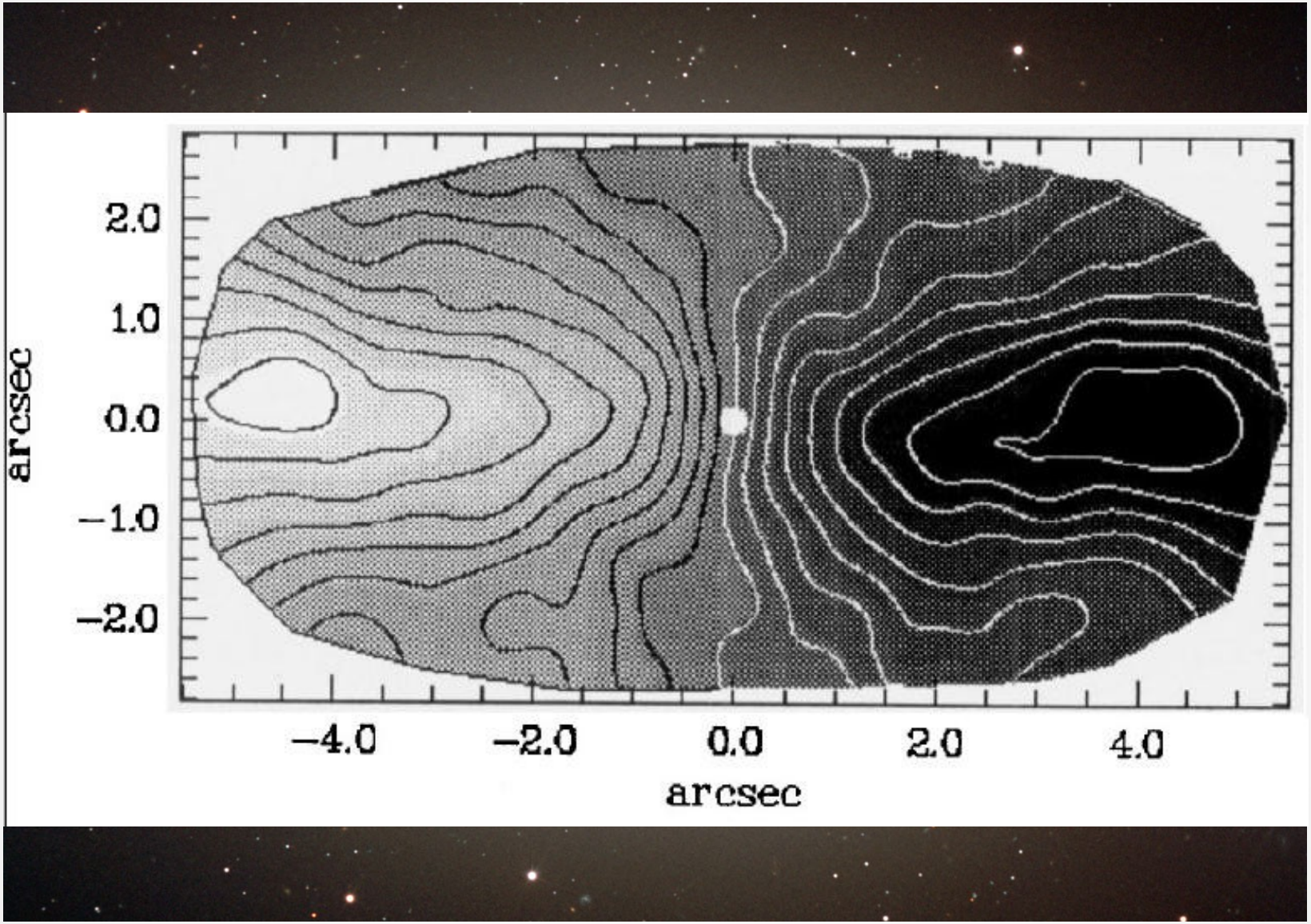

Emsellem et al. (1996)

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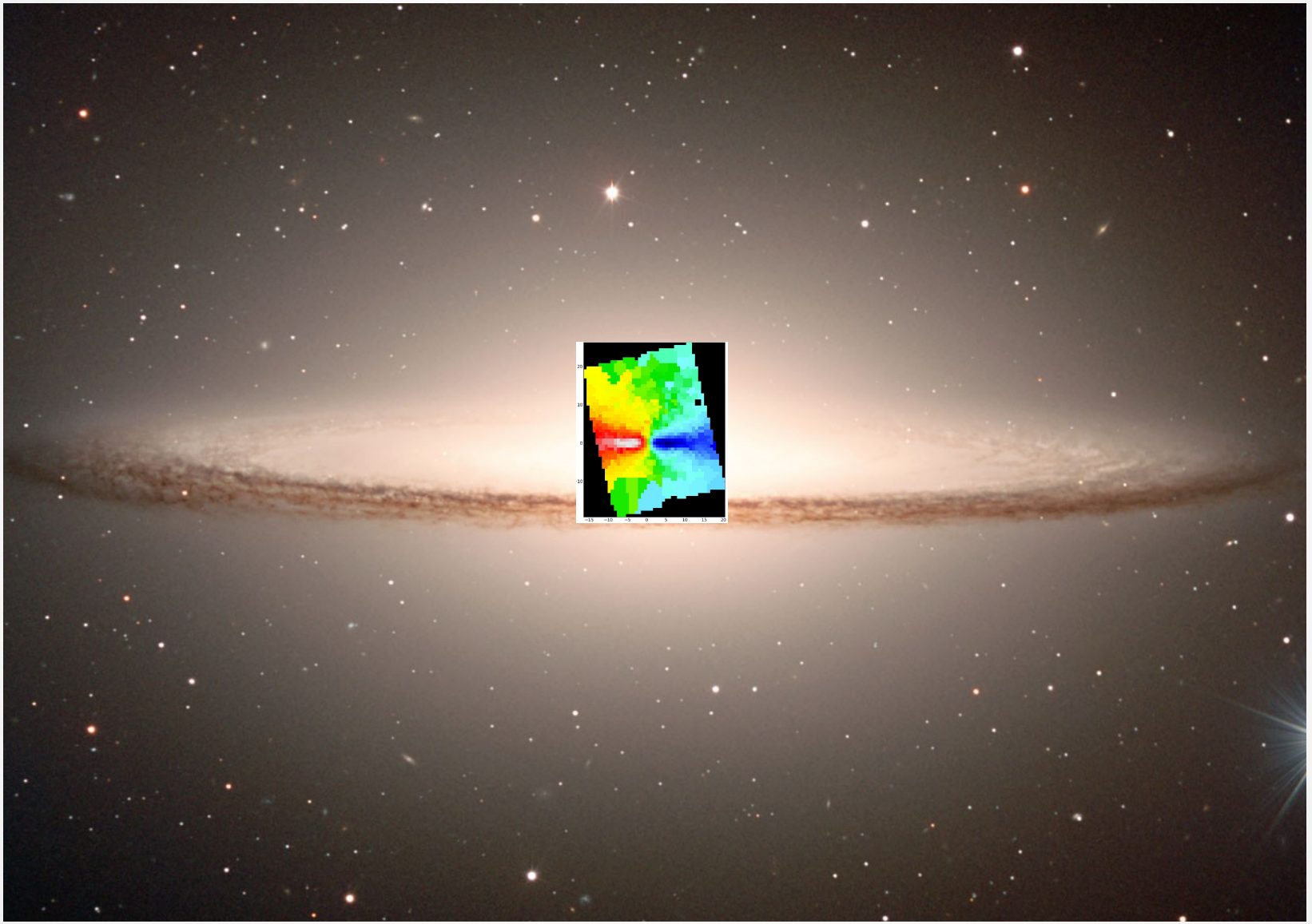

Sauron - 2003

Some impressions

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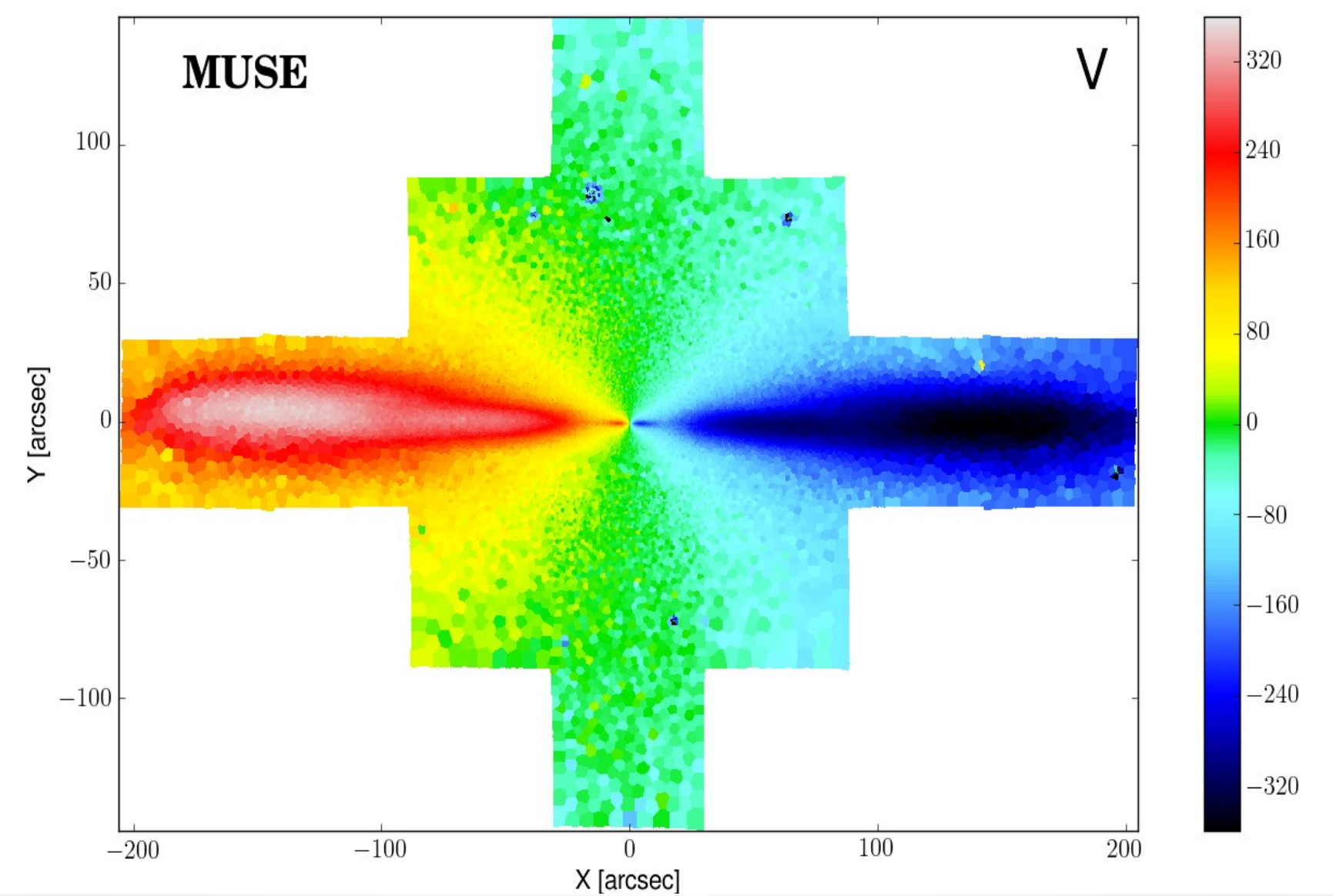

Emsellem et al. (2015)

Planned E-ELT instruments

- HARMONI
  - monolithic IFU
  - ~150x200 spaxels, sampling 4 – 30mas
  - NIR (0.8 – 2.4 μm), R > 3000
- METIS
  - single IFU module
  - 0.4“x1.5“ field of view
  - MIR (2.4 – 15 μm), R ~ 100000
- HIRES → talk by L. Origlia
- ELT-MOS
  - deployable IFUs planned

talk by S. Ramsey

The data reduction challenge

- DR software for IFS has a ambivalent history
  - „There is no DRS for instrument X...“
  - „The DRS for instrument Y does not work...“

- What makes it difficult?
  - CCD:
    - bias, dark, fringing, ...
  - spectroscopy:
    - trace the spectra, wavelength calibration, …
  - imaging:
    - flat-fielding, astrometry, …

Pipelines for IFS data

- The „Do-it-yourself“ epoch is over
  - working pipelines available for most instruments
    - ESO: http://www.eso.org/sci/software/pipelines/#pipelines_table

Instrument	Release Notes	Package	User Manual	Cookbook	Additional Documents	Additional Datasets	EsoReflex	Status
GIRAFFE	2015-04-15	2.14	2.14	Cookbook		Standard Calibration Files page		Operational on hold
KMOS	2015-06-23	1.3.13	2.16				Tutorial: 1.3 Demo Data: 1.1	Active
MUSE	2015-07-31	1.0.5	1.0.5			MUSE IFU 6 trace tables Leagacy MUSE static calibrations	Tutorial: 6.0 Demo Data: 1.2	Active
SINFONI	2015-09-14	2.6.8	19.4		ADA IV 2006 paper	Calibration Database Example (255 MB) Demonstration Package (1.2 GB)	Tutorial: 1.4 Demo Data: 0.2	Operational on hold
VIMOS	2015-08-04	2.9.16	6.10			Demonstration Package (1.7 GB)	Tutorial: 2.2 (VIMOS-IFU) Tutorial: 1.2 (VIMOS-MOS) Demo Data: 0.4	Active

    - p3d (Sandin et al. 2010): http://p3d.sourceforge.net/
    - ...
  - new instruments are extremely complex
    - reducing a MUSE cube requires 18GB of RAM

Typical data reduction tree

- Raw IFS data
  - subtract BIAS
  - subtract dark current
  - find the spectra
  - trace the spectra
  - wavelength calibration
  - spatial flatfield
  - construct the field of view
- Reduced IFS data

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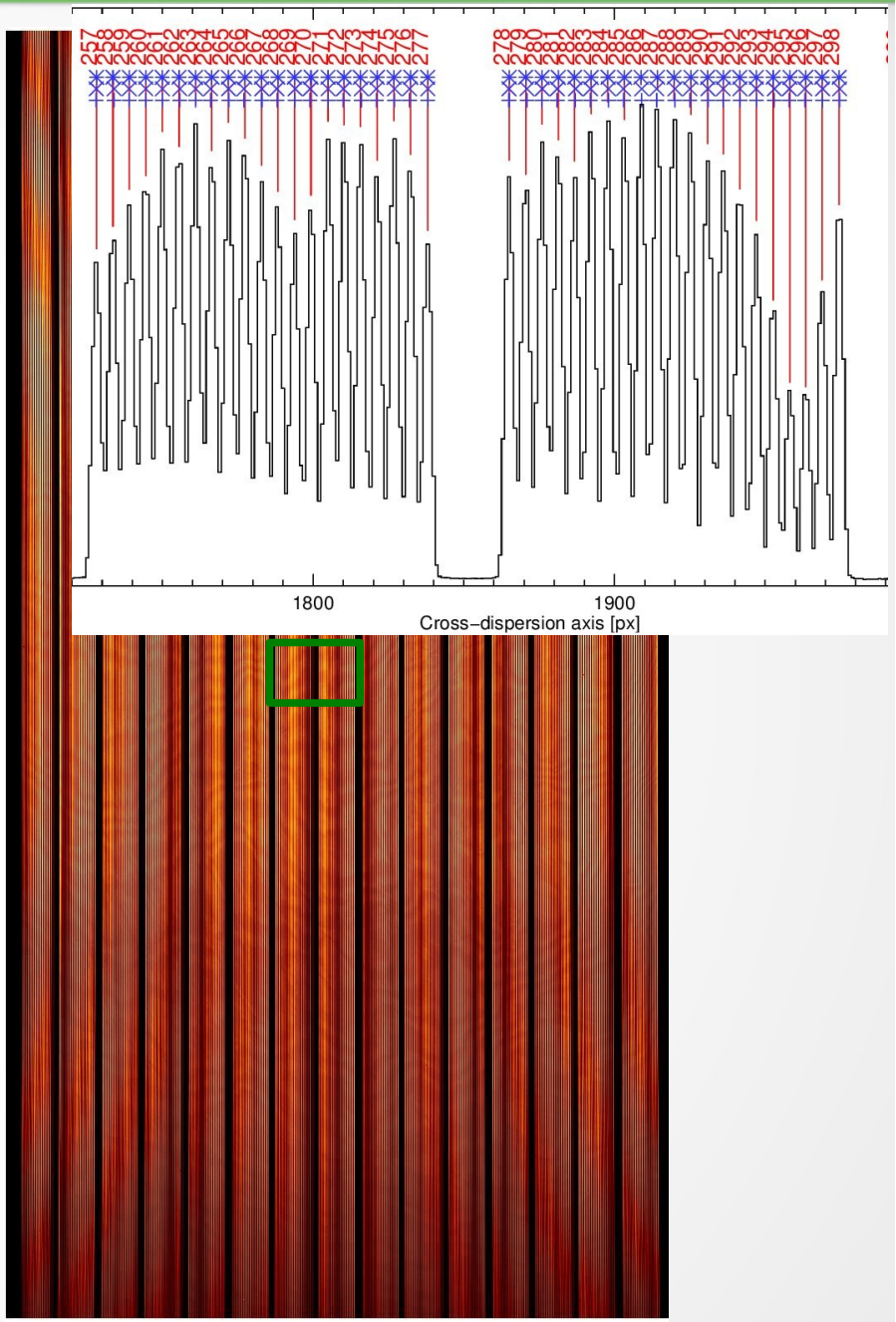

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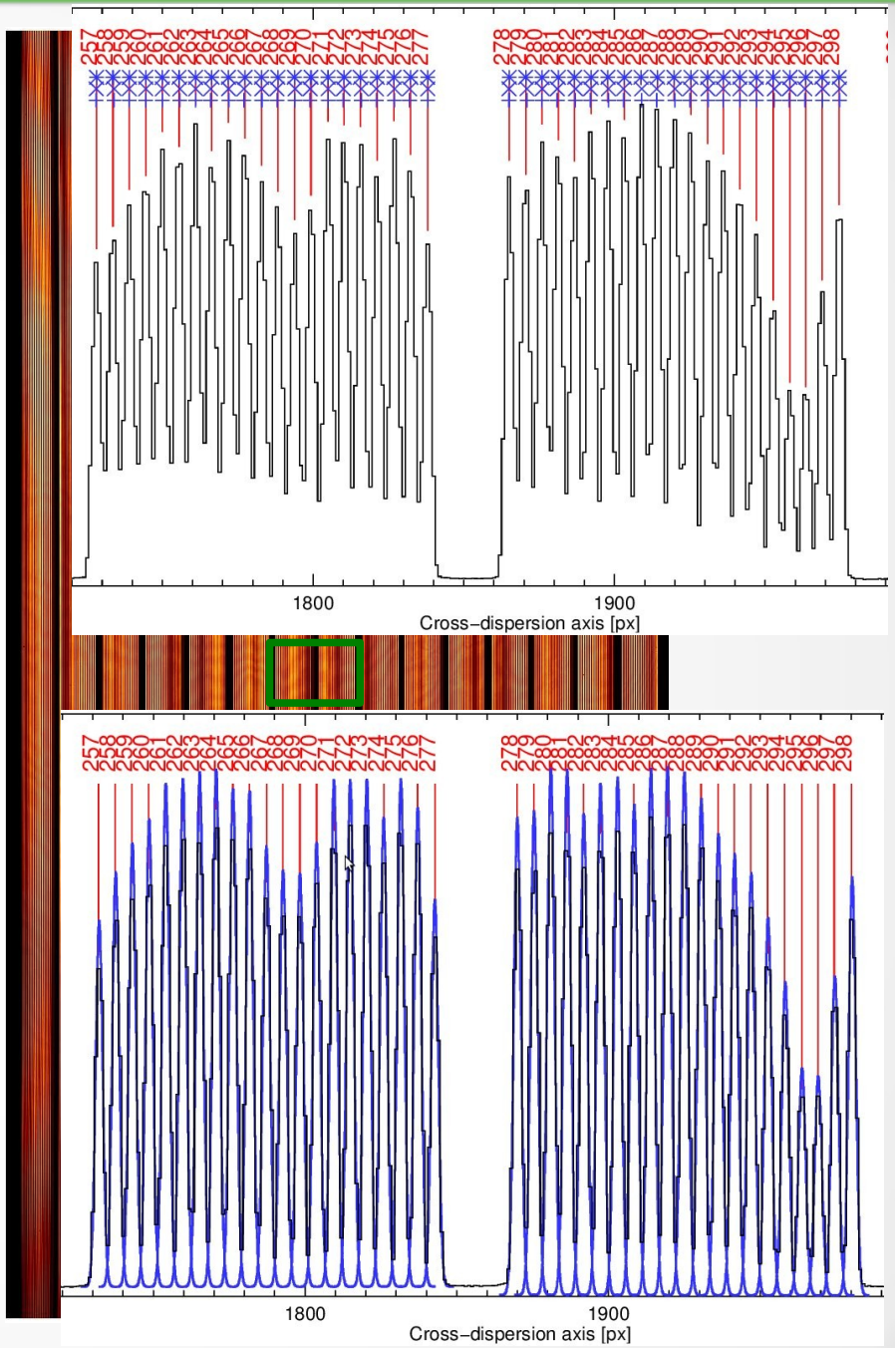

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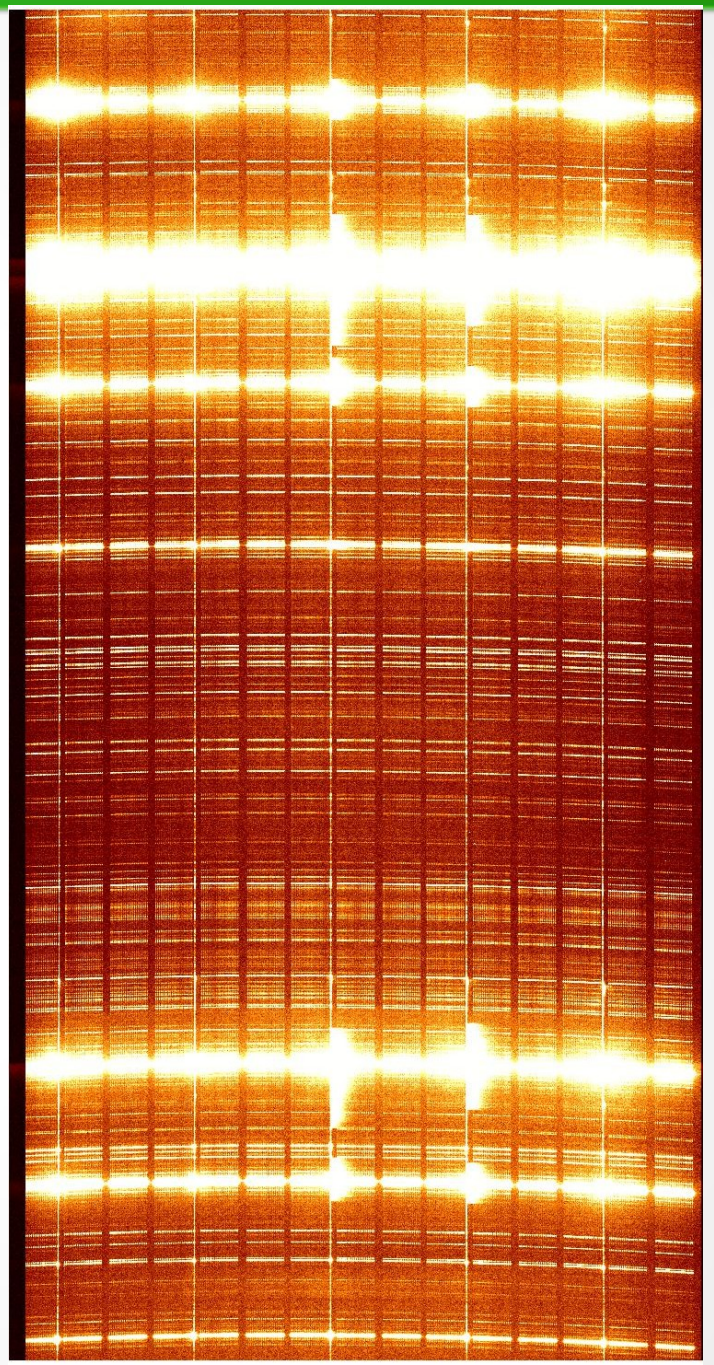

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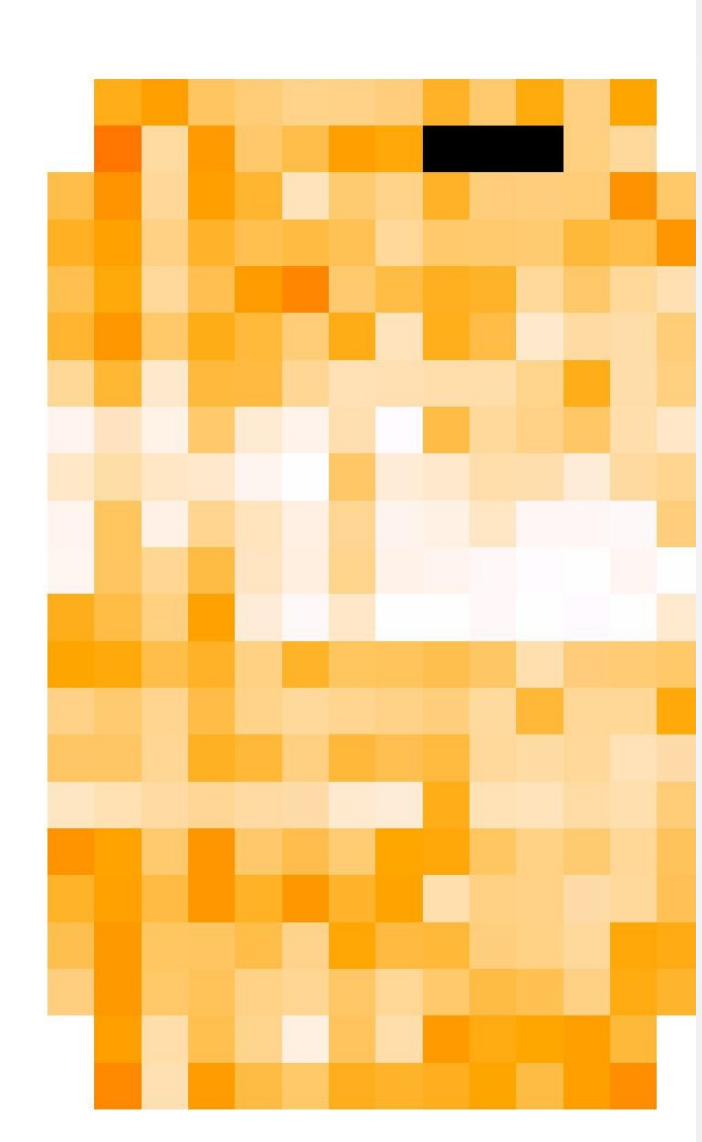

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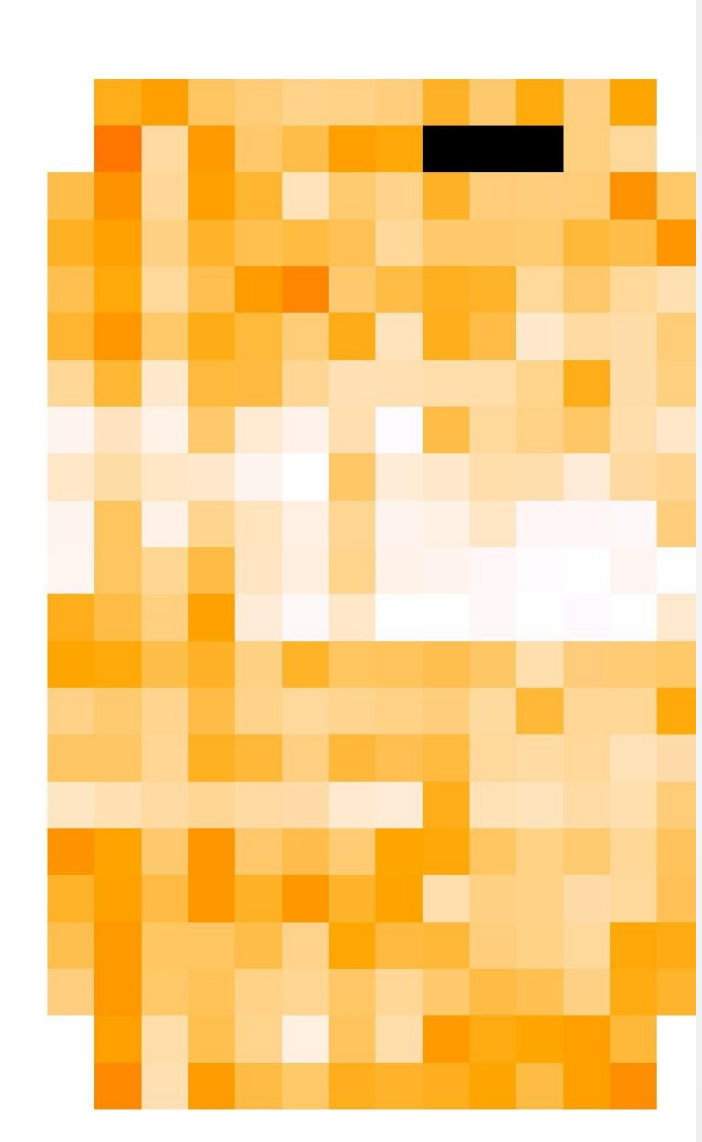
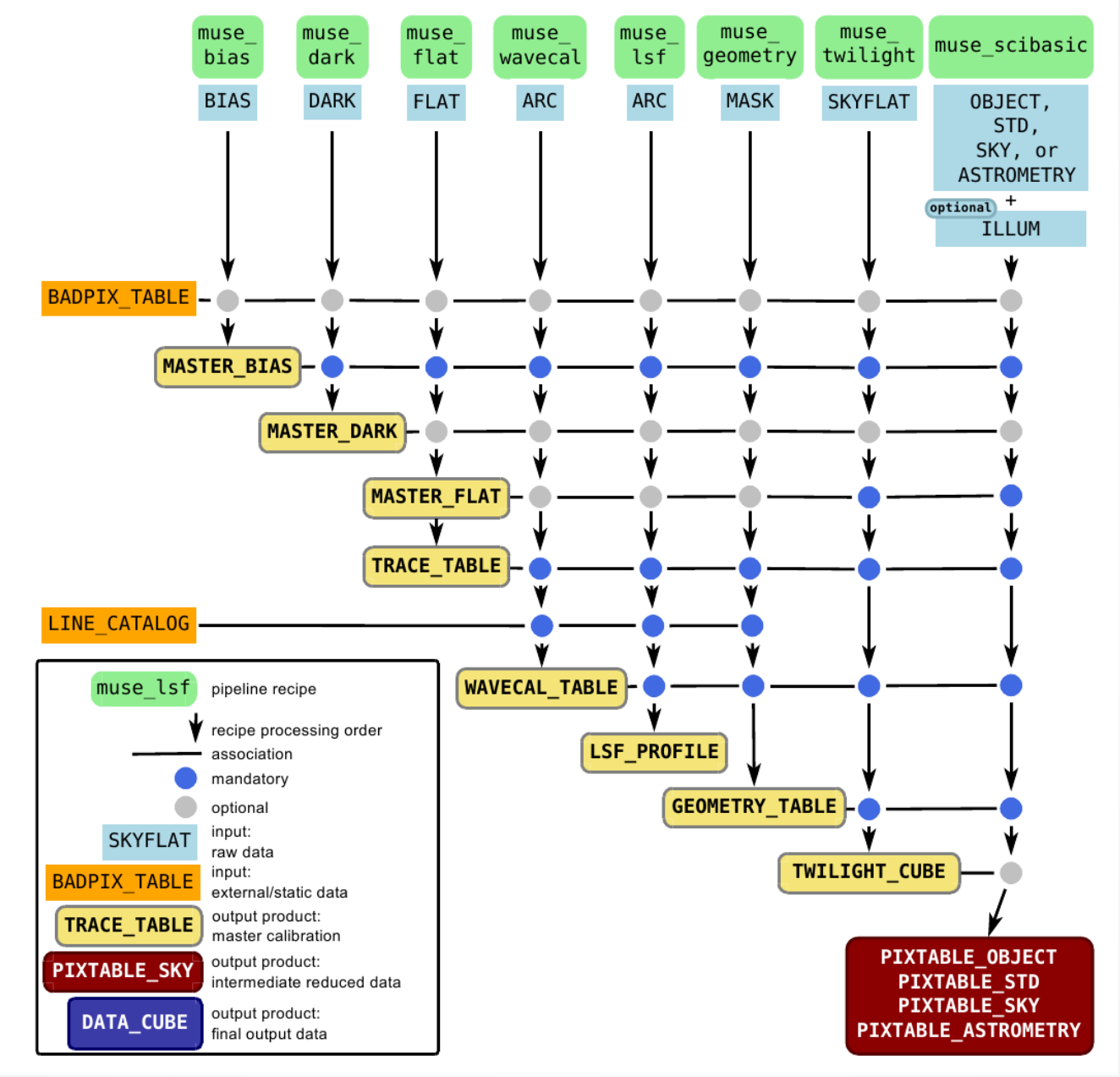


The MUSE reduction tree

per IFU:

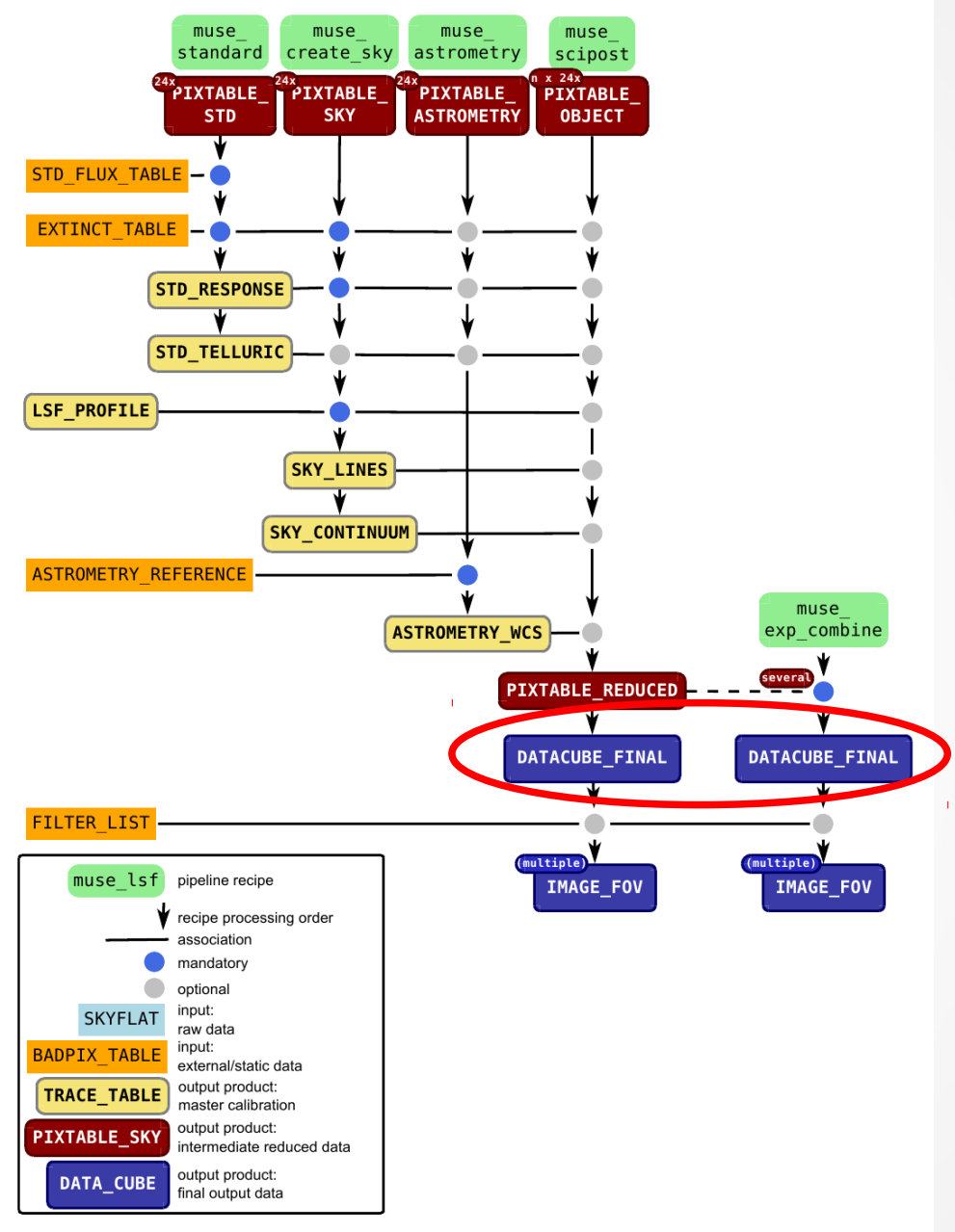


x24

credit: P. Weilbacher

The MUSE reduction tree

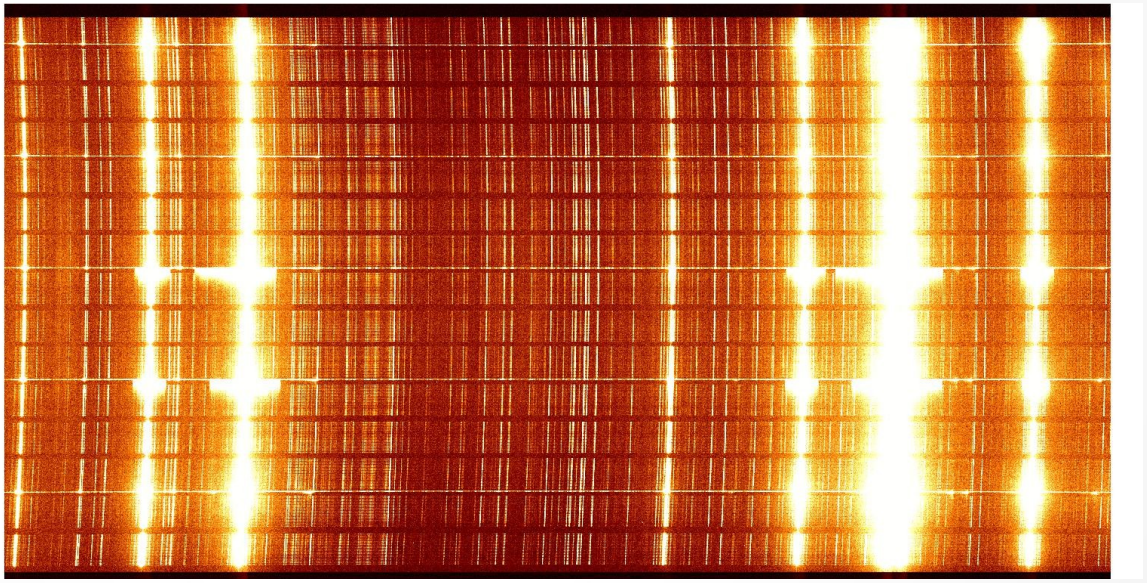
combine IFUs:



credit: P. Weilbacher

The output format

- Instruments do NOT produce datacubes!
  - spaxels are not quadratic
  - filling factor of field of view <1
  - fibres/slices have different disperions:

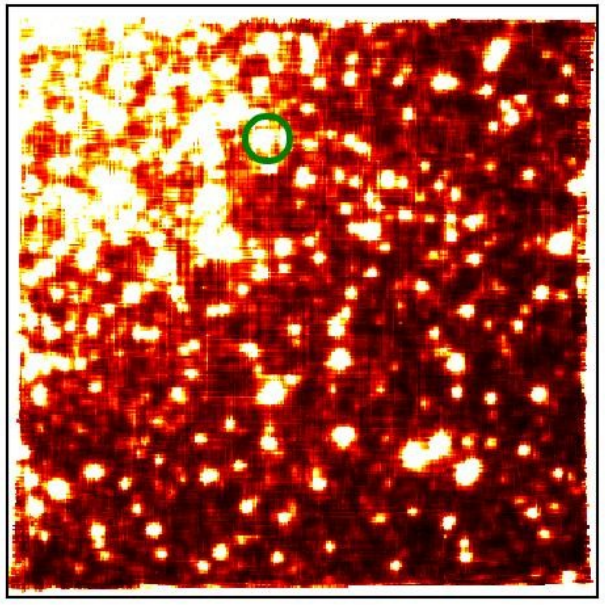


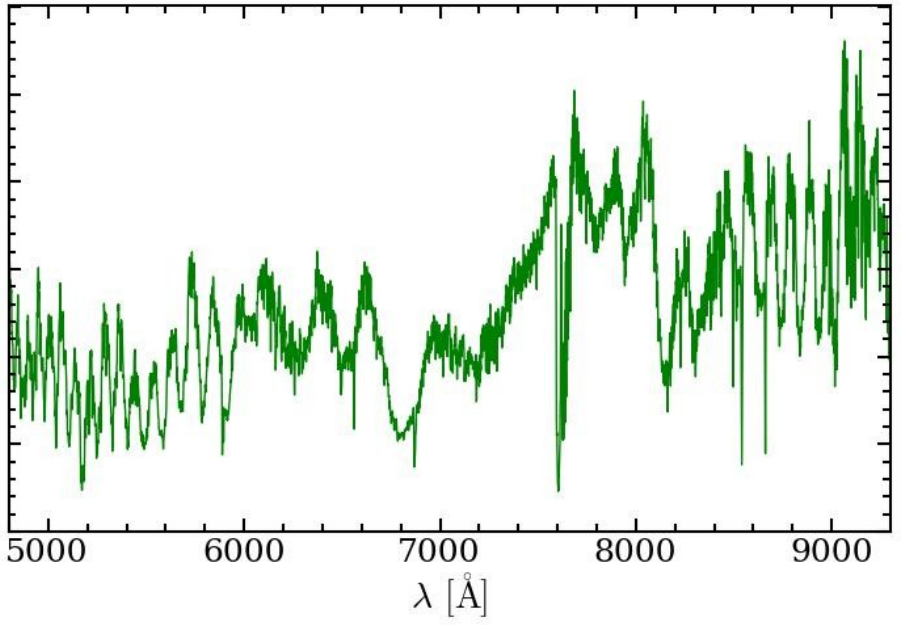
→ irregularly sampled 3dim. structure

→ creating a cube requires resampling

The output format

- Problems of resampling:
  - may introduce artefacts
  - error propagation
    - correlations between adjacent pixels
    - pipeline usually neglects covariances
    - variance spectra show wiggles:





Alternative output format

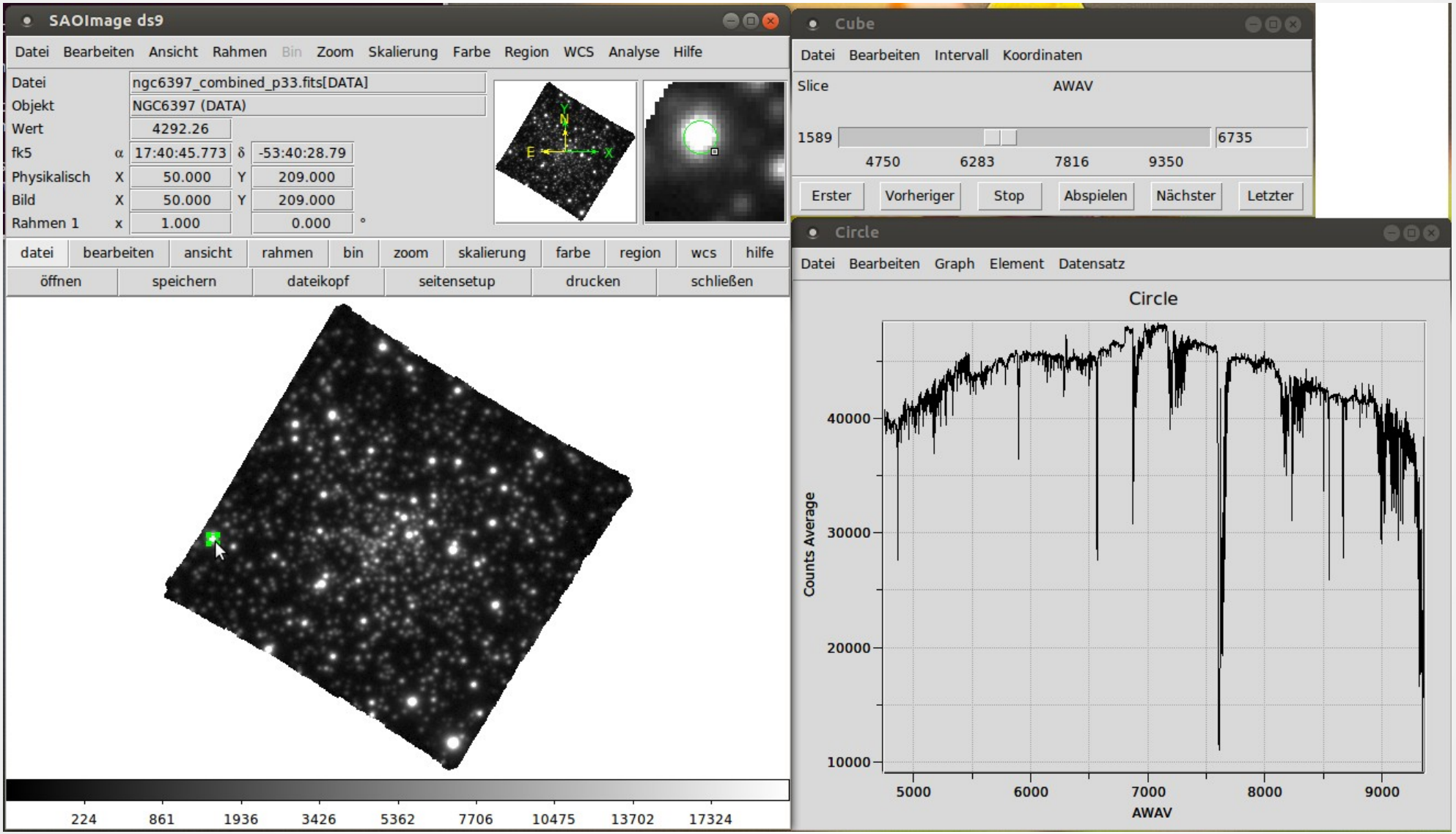
- Pixtables (e.g. MUSE Pipeline):
  - all calibrations are applied to the raw pixels
  - saved as gigantic pixtable:

RA	DEC	LAMBDA	FLUX	ERROR
-33.456	55.901	4555.0	1234.1	244.2
-33.455	55.913	4555.1	1121.1	255.6
-33.453	56.097	4554.9	1432.7	456.6
-33.453	56.098	4554.7	NaN	NaN
...	...	...	...	...

  - Advantage: No resampling needed
  - Disadvantage: Almost no programme can use it...

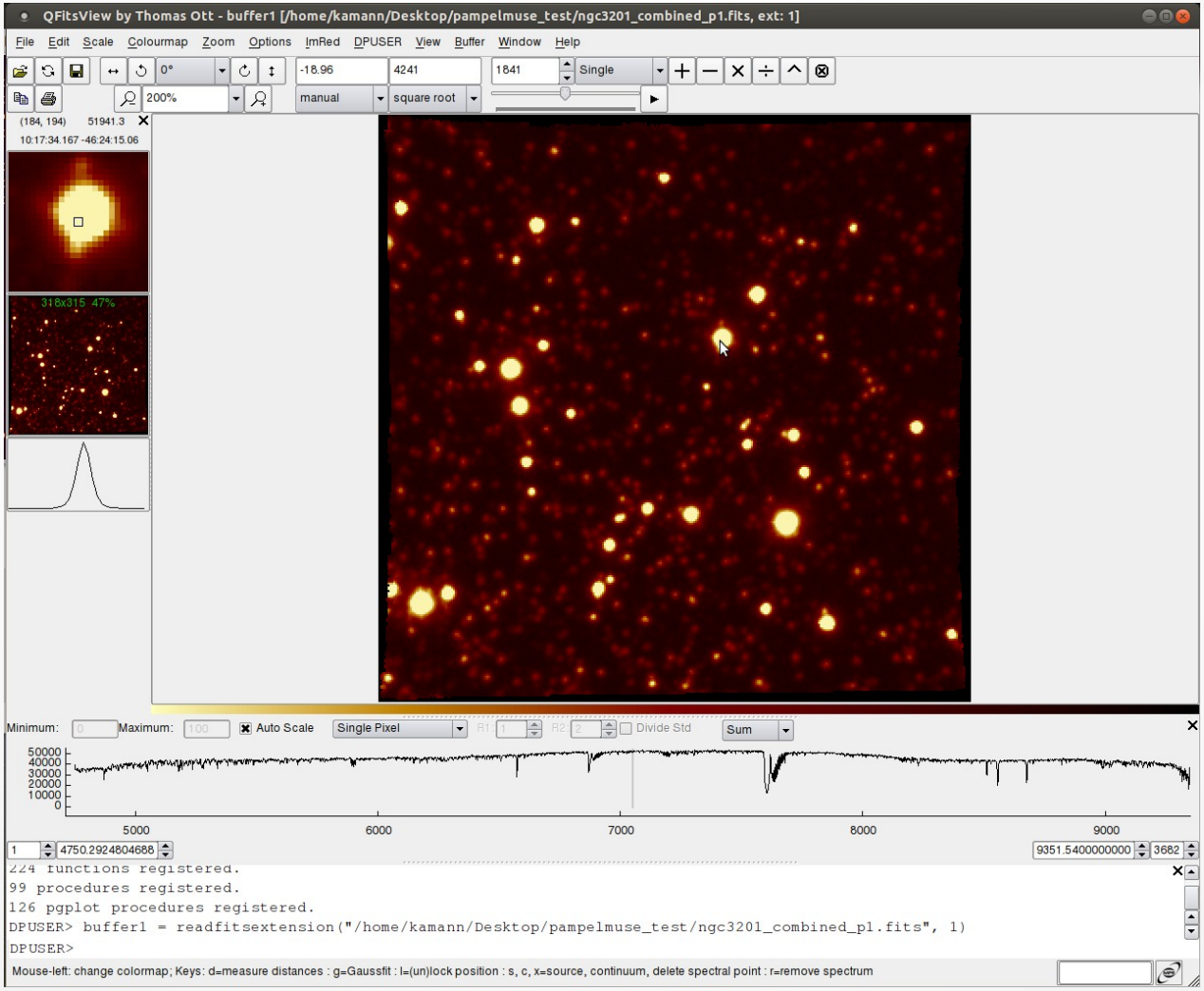
Some useful tools

- ds9 – http://ds9.si.edu/site/Home.html



Some useful tools

- ds9 – http://ds9.si.edu/site/Home.html
- QFitsView – http://www.mpe.mpg.de/~ott/QFitsView/



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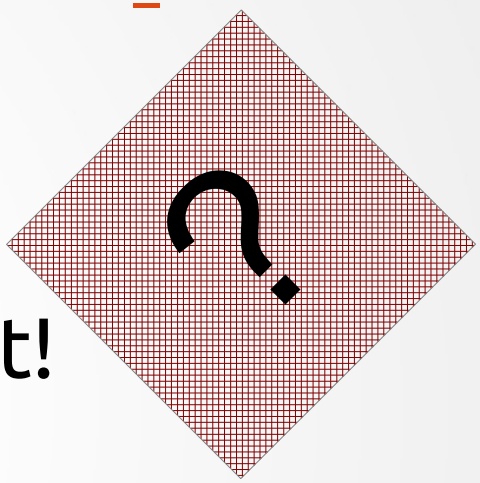
- see IFS Wiki (http://ifs.wikidot.com/) for more about
  - instruments
  - data reduction
  - data analysis tools

„Homework“

- A datacube is waiting for you at:

  http://www.astro.physik.uni-goettingen.de/~skamann/student_cube.fits

- Your tasks (until my second talk):
  - ✔ Download it!
  - ✔ Open it with ds9, get familiar with it!
  - ✔ How many stars do you find?
  - ✔ For how many of them can you get a clean spectrum?
  - ✔ For how many of them could you get a clean spectrum with a fibre of diameter 2.0“?



Conclusions

- Integral field spectroscopy is a powerful tool
- Very rapid development in last ~20 years
- Huge variety of instruments ready for great science
- We understand the data and can handle it
- My provocative input for your dinner discussion:
  - „In my (biased?) opinion, integral field spectrographs will be the most important instruments for the E-ELT!“