Jacopo Fritz, IRyA - UNAM

DataCubes in Astrophysics

Lesson 1

WELCOME!

Who am I?

- Jacopo Fritz - Italian;
- Currently professor at Instituto de Radioastronomía y Astrofísica (IRyA)- UNAM, Morelia, Mexico;
- PhD at Padova University, 2005 (“*Analysis and modeling of active galaxies from optical to infrared*”);
- Postdocs on galaxy evolution in clusters at Padova National Observatory;
- Postdoc on spectral modeling at University of Bologna;
- Postdoc on Herschel data reduction and exploitation at Ghent University (Belgium).

WELCOME!

My research interests

- ✓ Modeling of IR emission in AGN;
- ✓ Dust properties of galaxies;
- ✓ Spectral synthesis and modeling of galactic spectra;
- ✓ Galaxy evolution in clusters.

How will this work?

- I will present you with tools, software, theoretical background;
- whatever you do not understand, you MUST ask, and we will discuss it;
- learning (and teaching) is much more fun if it's interactive;
- so: interrupt me for questions, comments;
- I will do the same, of course!

Datacubes Handling in Astronomy

Various type of datacubes

Review (or learn) the physics related to these observations

Learn how to deal with (some of the formats of) astronomical data in 3D

Learn (some of) the techniques and tools to analyze these data

Extract all possible information

THE PROJECT: write a paper!

What will we need?

- Python (with some important libraries);
- pPXF (standalone python package from Cappellari, 2017);
- SINOPSIS (Fortran code from Fritz et al. 2017);
- DS9 (SAOImage);
- python general tools for cubes are also available.

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The lessons (1)

- Basic concept of spectroscopy;
- introduction to Integral Field Units (optical);
- datacubes from Radiative Transfer simulations;
- brief introduction to AGNs and their IR emission;
- dust radiative transfer techniques;
- **Task 1**: dealing with RT simulations cubes.

The lessons (2)

- Atomic and molecular gas emission mechanisms;
- from emission to column densities;
- **Task 2**: analysis and manipulation of CO and HI cubes;
- IR emission from dust;
- IR telescopes and observing techniques;
- the Herschel Science Archive (HSA);
- Detailed flux uncertainty calculation for Herschel's photometers.

The lessons (3)

- **Task 3**: analysis and manipulation of Herschel images.
- Convolution and pixel-matching (regridding);
- **Task 3.5**: calculate the total and the spatially resolved gas-to-dust ratio for M51;
- spectral lines: brief review of the emission processes (all wavelengths);
- important lines across the whole electromagnetic spectrum (and their use).

The lessons (4)

- Datacubes in the optical: IFU units;
- the physics behind a IFU analysis;
- the Doppler effect;
- stellar and gas dynamics;
- dust extinction;
- Star Formation Rate calculation;

The lessons (5)

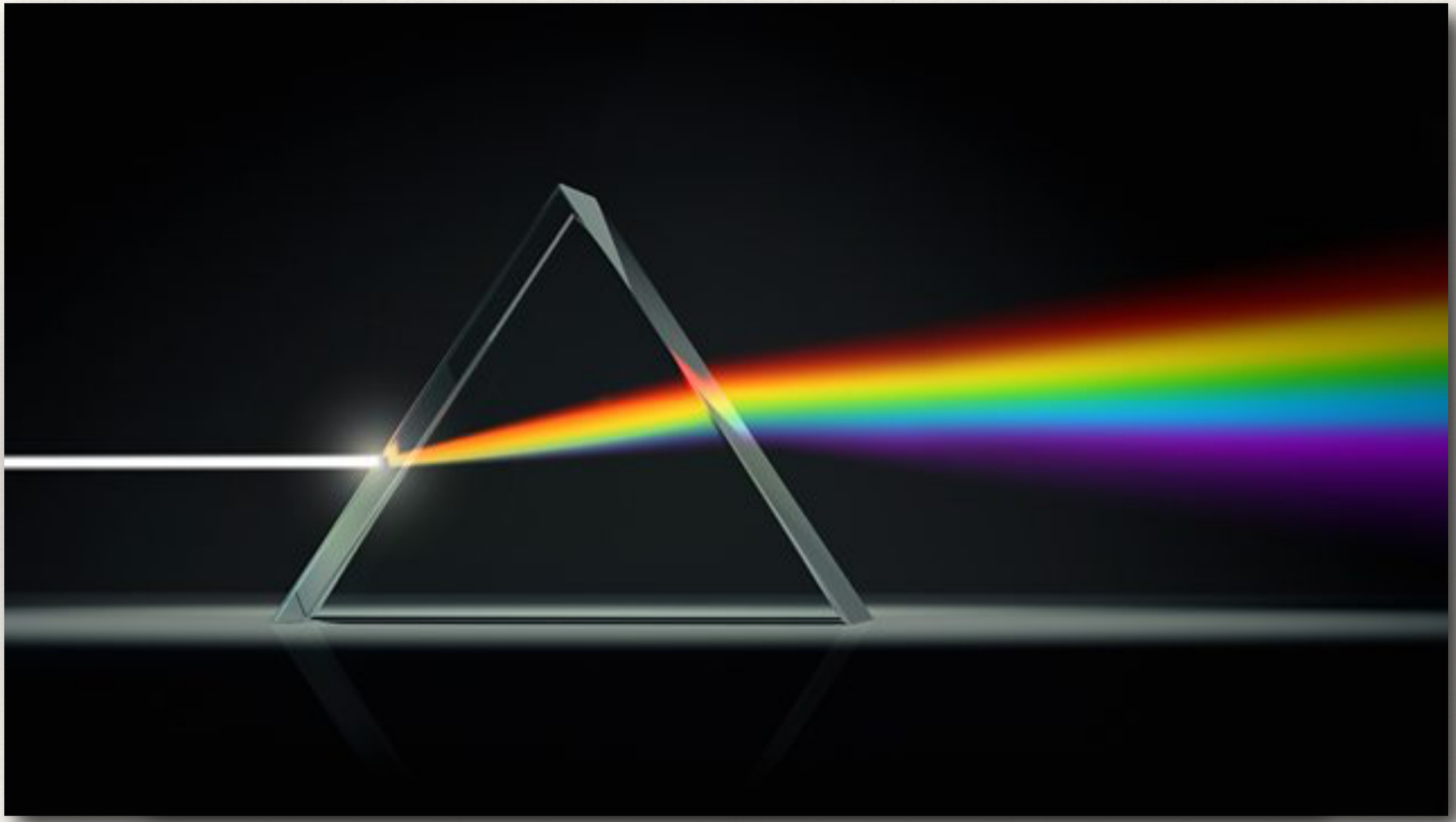
- Galactic spectra;
- stellar population synthesis techniques;
- introduction to SINOPSIS;
- galaxy evolution in clusters: basic concepts;
- **Task 4**: a complete analysis of a galaxy observed with MUSE.

The lessons (6)

- Redaction of a project:
    1. description of the data;
    2. description of the tools;
    3. results;
    4. interpretation.

Let’s Get Started!

It's (mostly) about spectroscopy



Spectroscopy

Is a technique, used in various fields of science, that allows us to measure the intensity of light as a function of its frequency (wavelength).

What is this for?

On the subject of stars, all investigations which are not ultimately reducible to simple visual observations are […] necessarily denied to us.
While we can conceive of the possibility of determining their shapes, their sizes, and their motions, we shall never be able by any means to study their chemical composition or their mineralogical structure.

Auguste Comte, 1835
Course de la Philosophie Positive

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EPIC FAIL!!!

Auguste Comte, 1835
Course de la Philosophie Positive

“Classic” spectroscopy

- Point the telescope to the most amazing object in the sky;
- on the focal plane, put a closure (a slit), centered on the object;
- send light to a dispersive tool (prisma, grating grid);
- this creates a “monochromatic” image of the slit at various wavelength;
- record the signal onto a CCD.

Observables

What are we measuring?

- A spectrum is a light intensity (flux) measured as a function of wavelength;
- it has a continuous sampling;
- the *spectral resolution* (see next) depends on the instrument configuration.

Spectral resolution

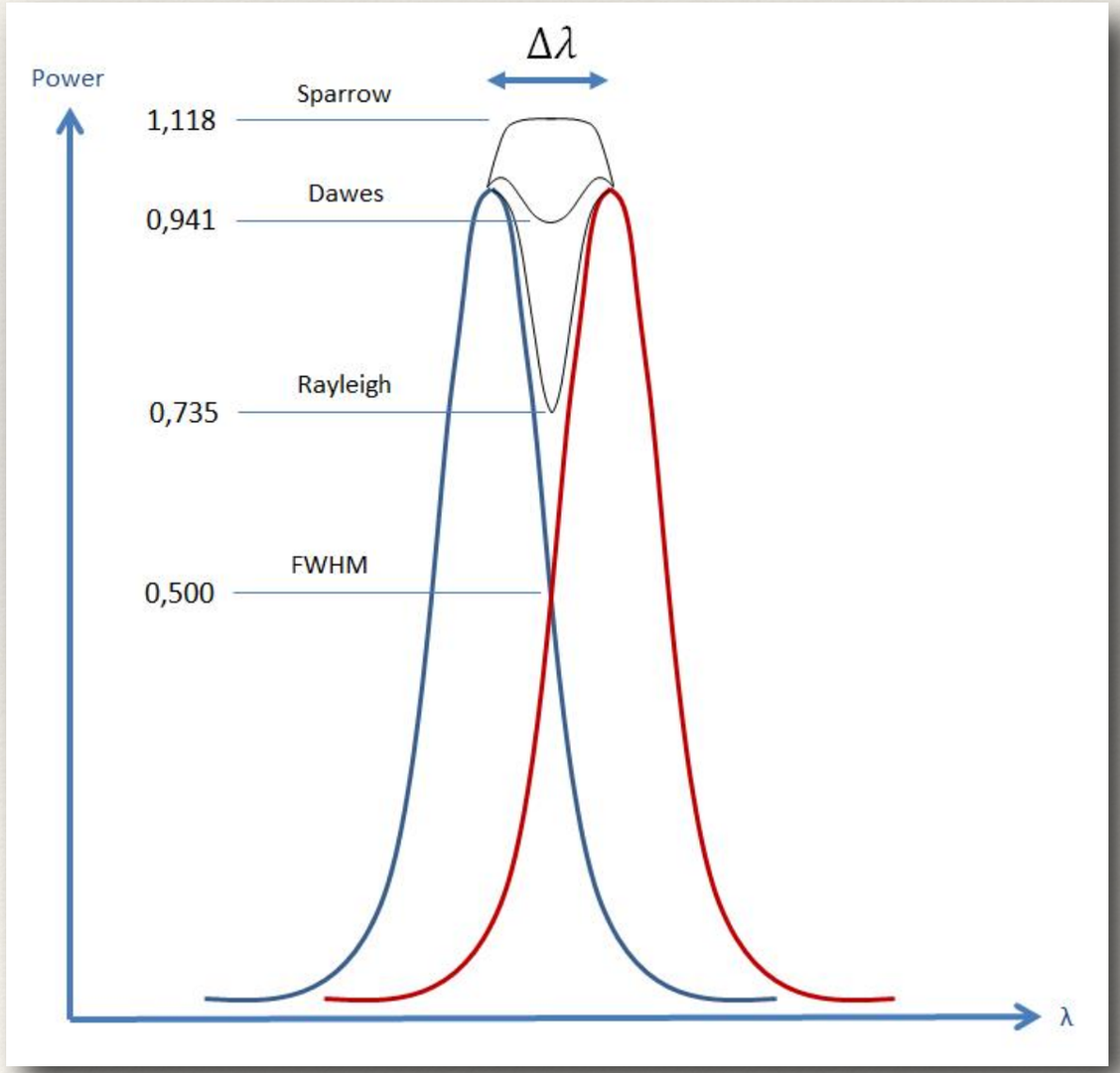
Is the smallest detectable separation between the emission at two wavelengths

Various criteria can be used:

The Rayleigh criterion:

two images are just resolvable when the center of the diffraction pattern of one is directly over the first minimum of the diffraction pattern of the other.

$$\theta = 1.22\frac{\lambda}{D}$$



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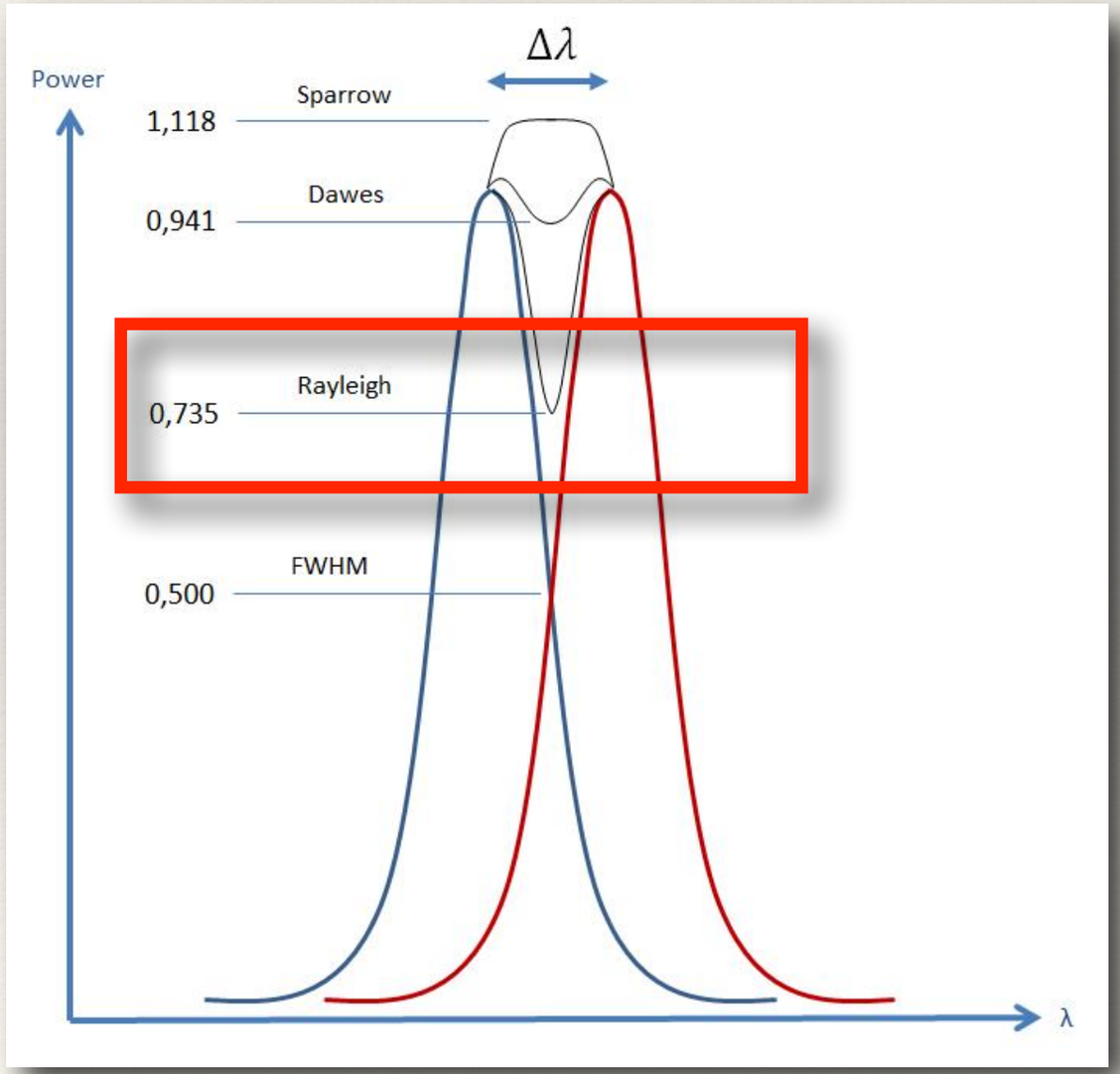
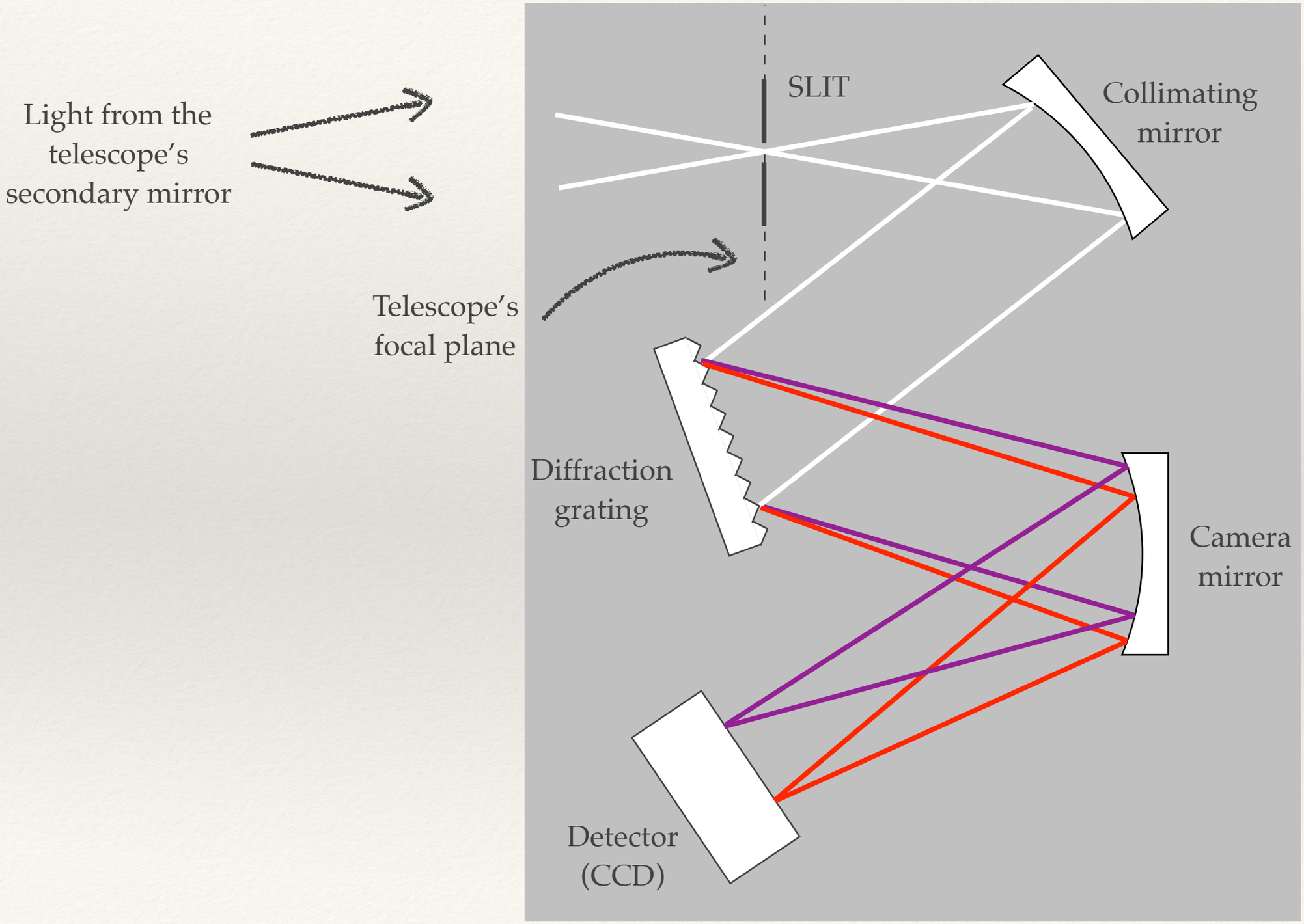


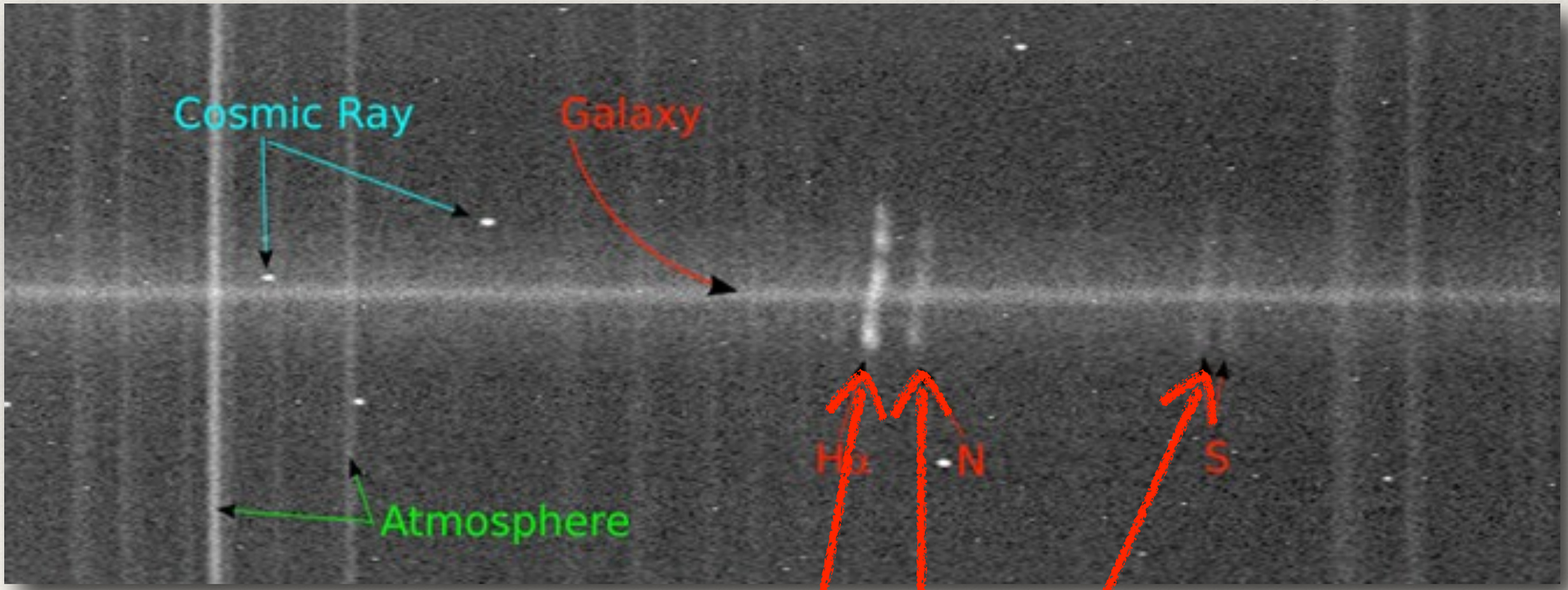
“Classic” spectroscopy



“Classic” spectroscopy

“Sky” lines

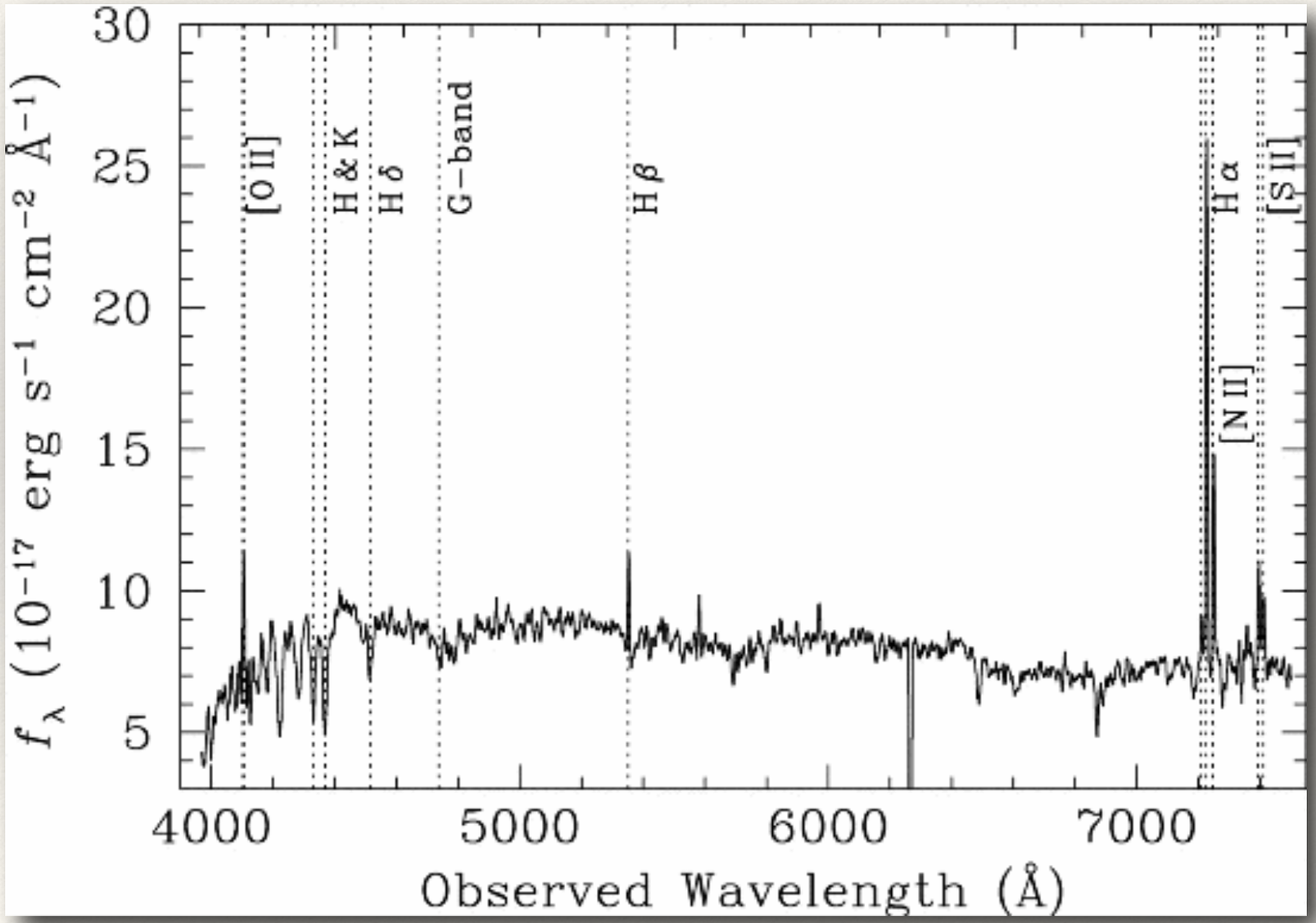
Continuum



“Real” spectral lines

“Classic” spectroscopy

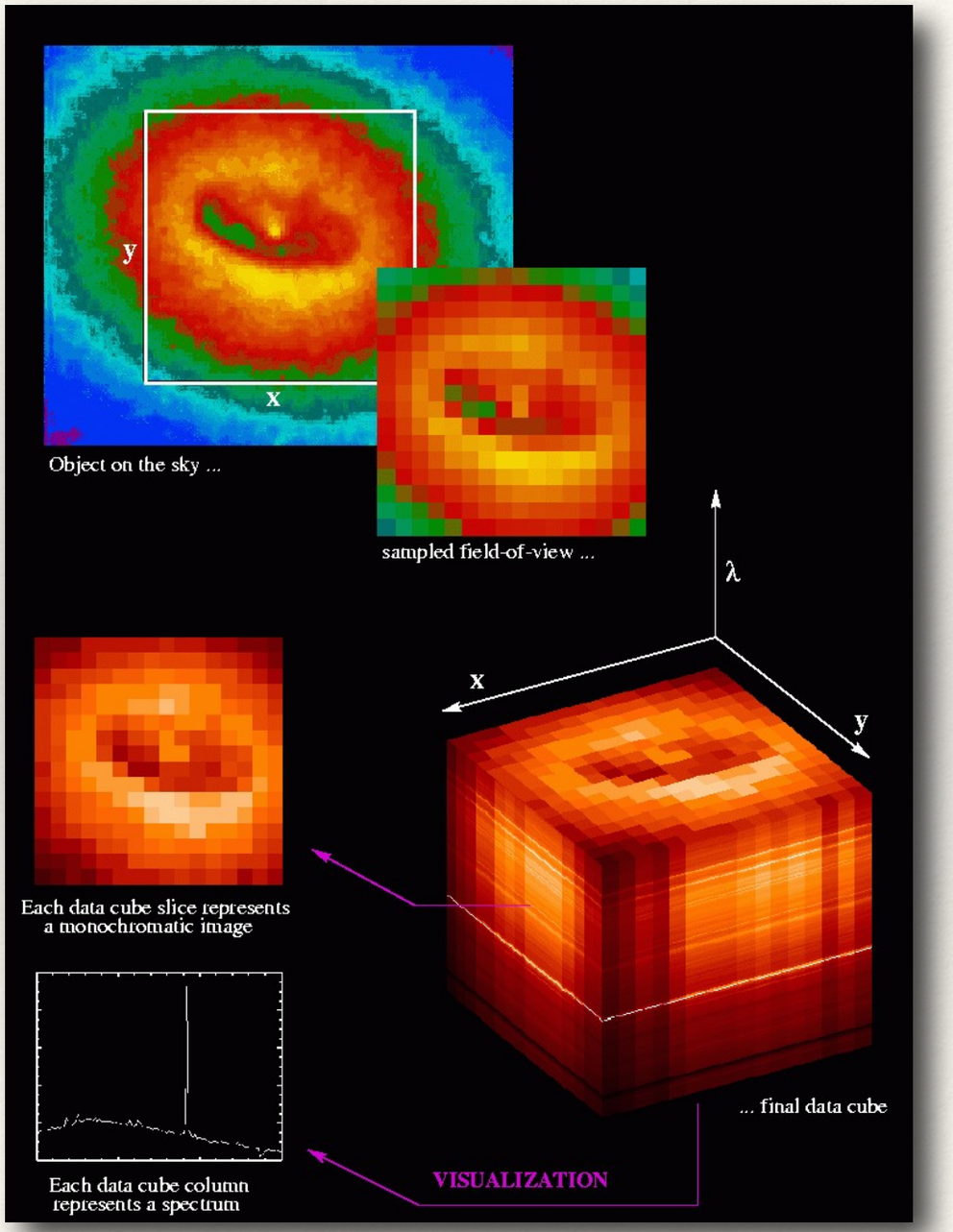
When collapsed along the y-axis direction:



Datacubes in Astronomy

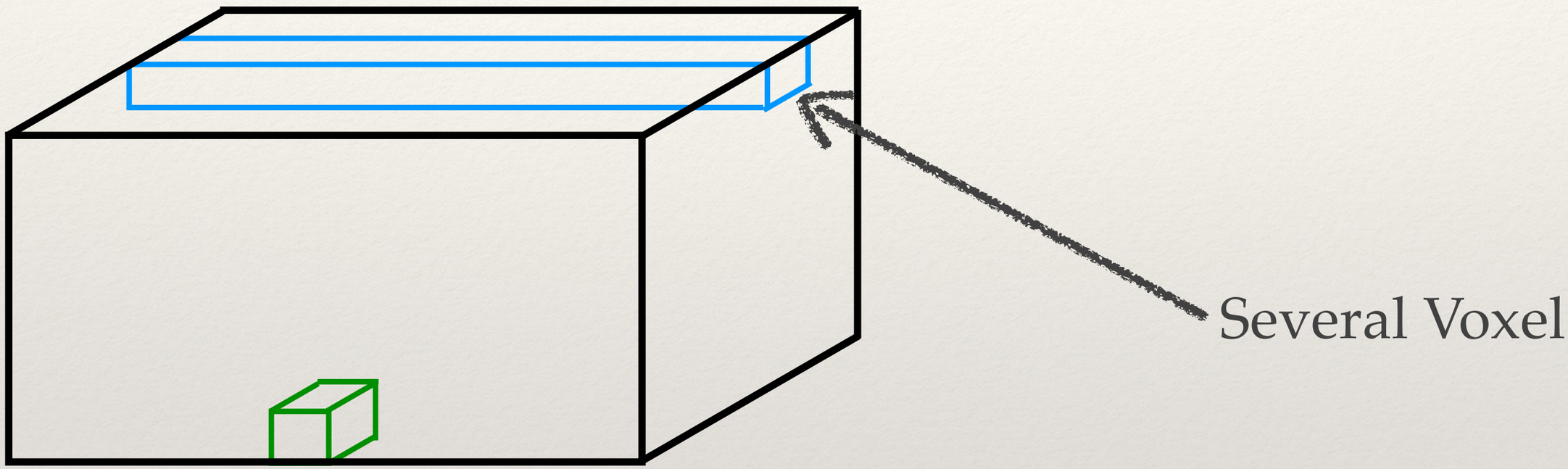
- Integral Field Units (Optical/Infrared);
- Radio & Sub-millimeter observations;
- Time-domain (X-rays);
- Spatially resolved broad-band SED.

Integral Field Units (IFUs)



- A combination of *imaging* and *spectroscopy;*
- the outcome is a 3-dimensional dataset;
- provides spatially-resolved physics;
- quite time “expensive”.

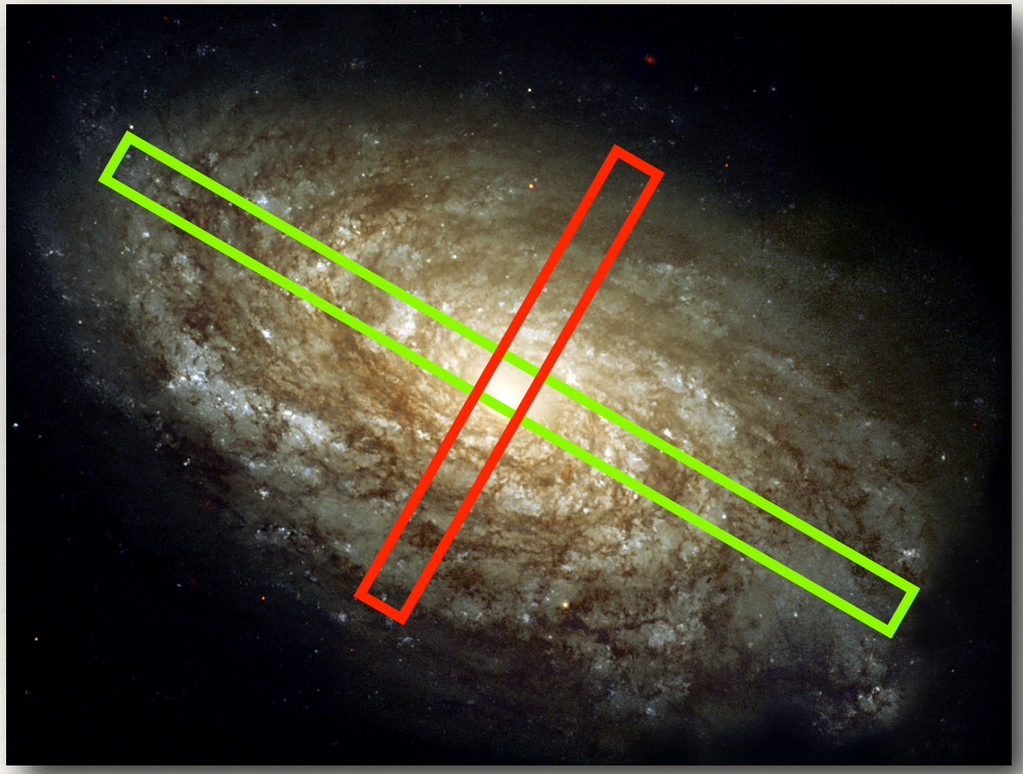
IFU constituents



- ✓ Pixel: a point on a CCD
- ✓ Spaxel: a spectrum on a datacube
- ✓ Voxel: datapoint of a data cube

Why using IFUs?

"Slit spectroscopy"



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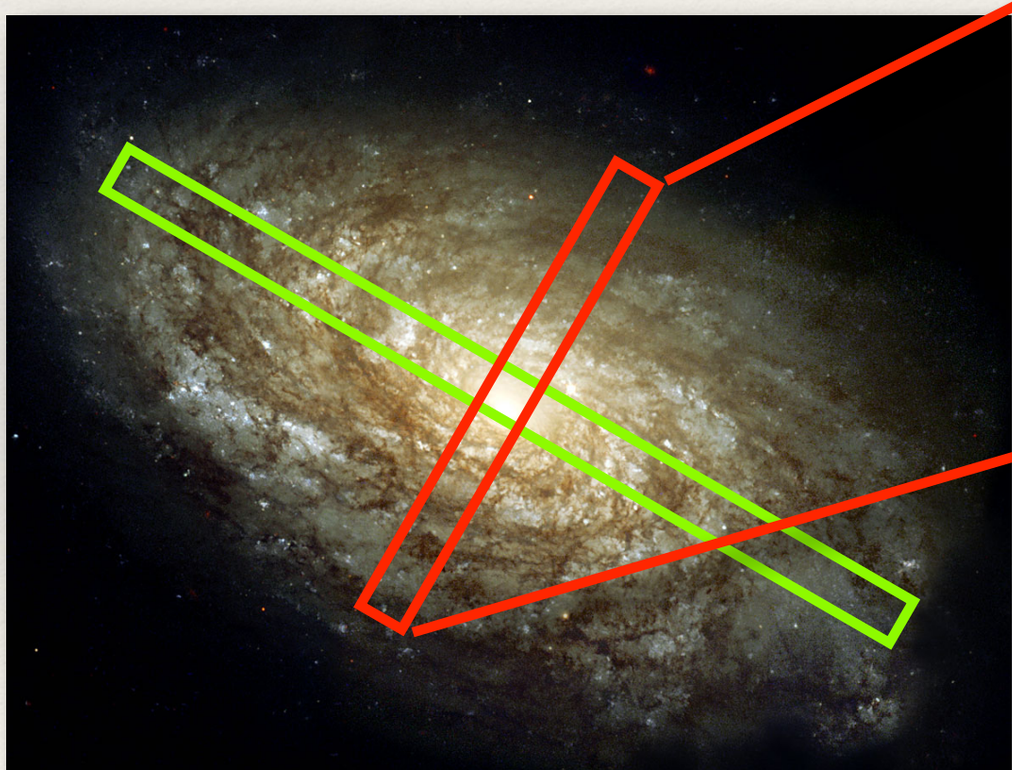

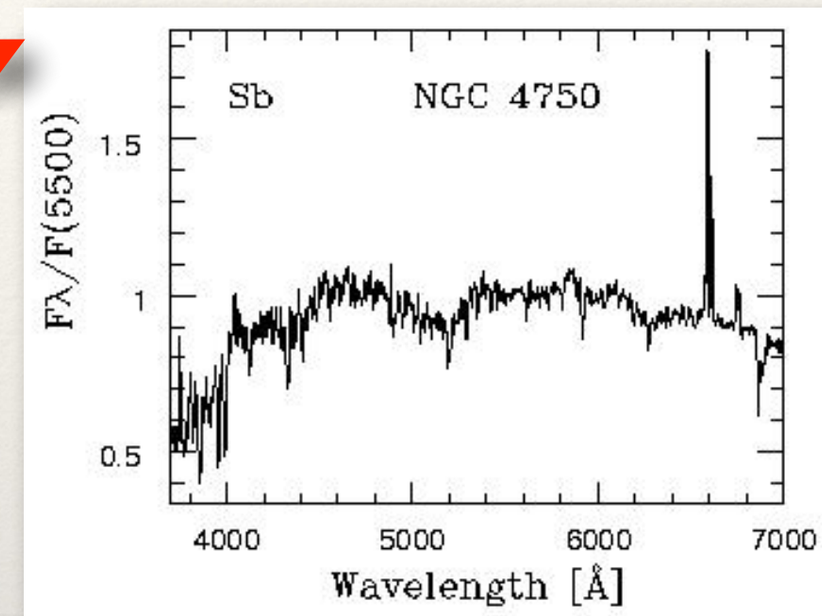

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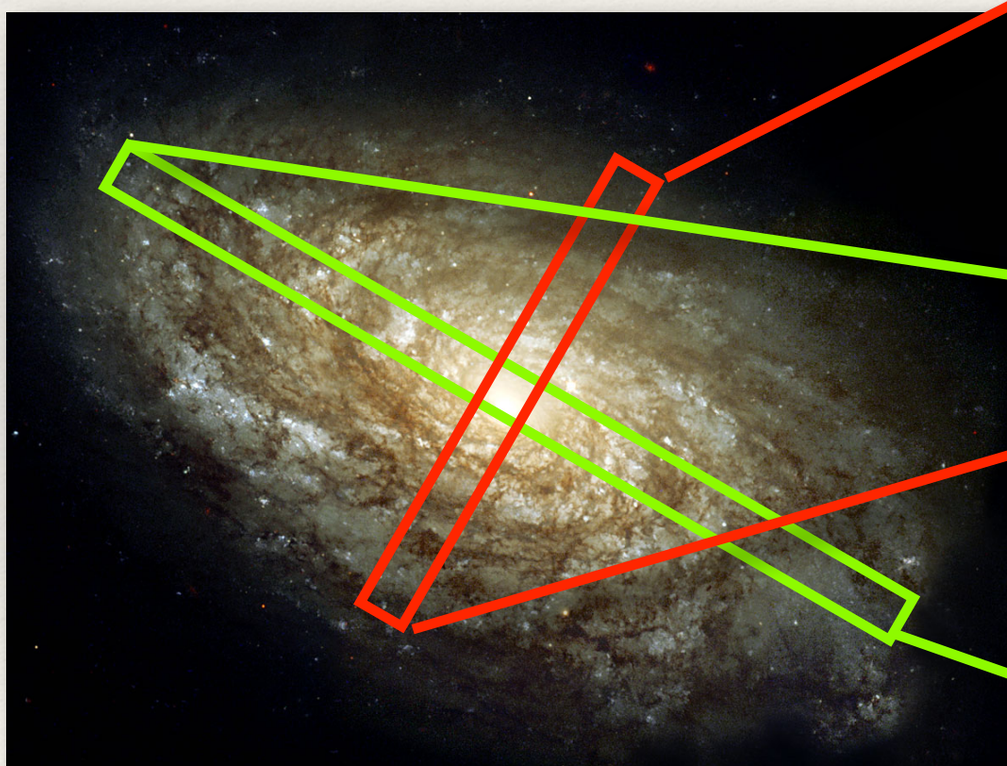

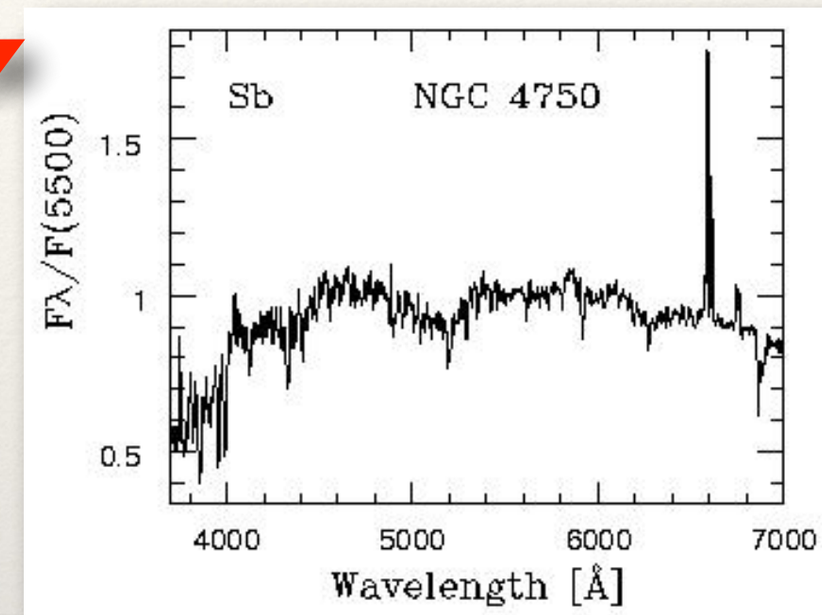

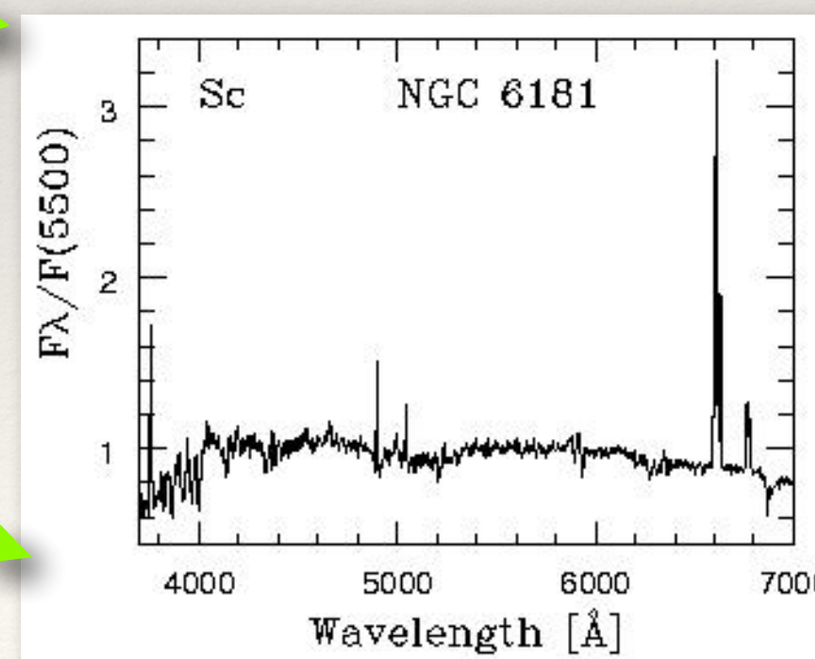

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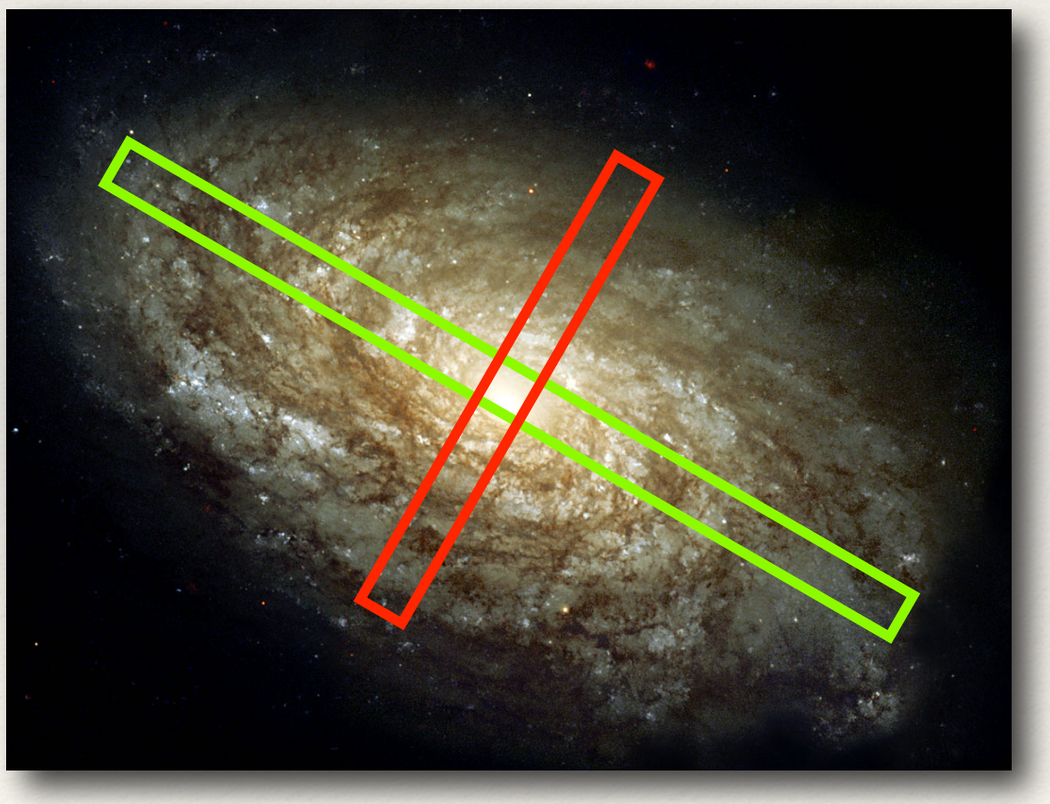

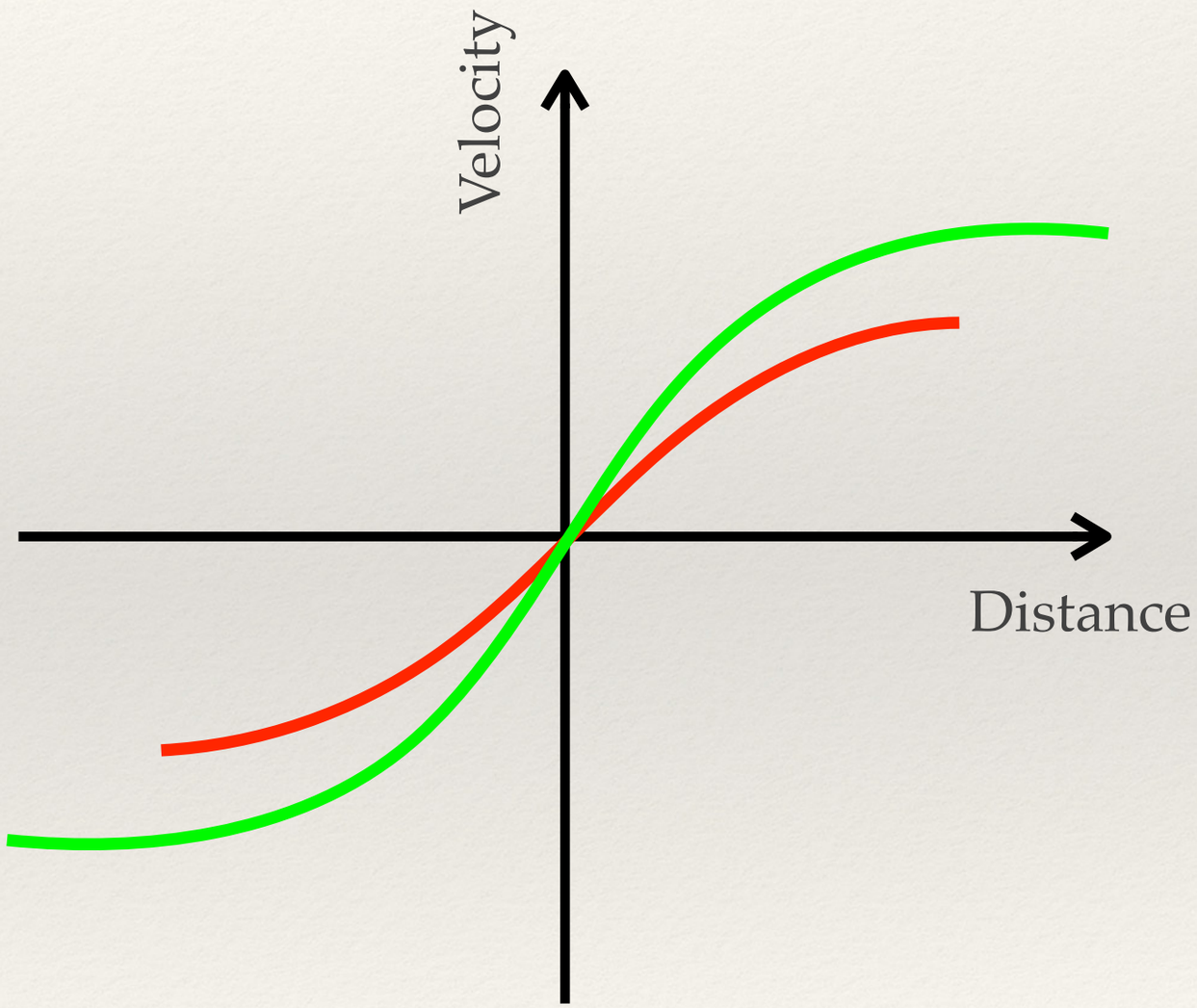

Why using IFUs?

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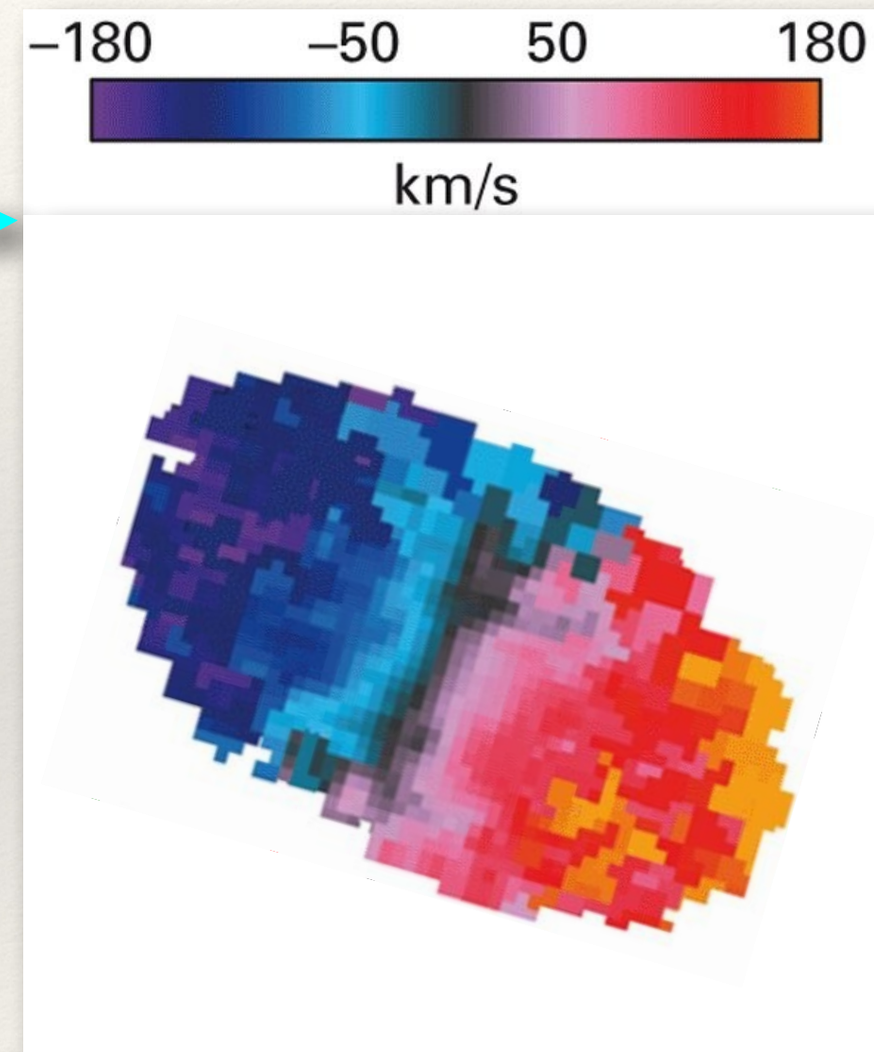

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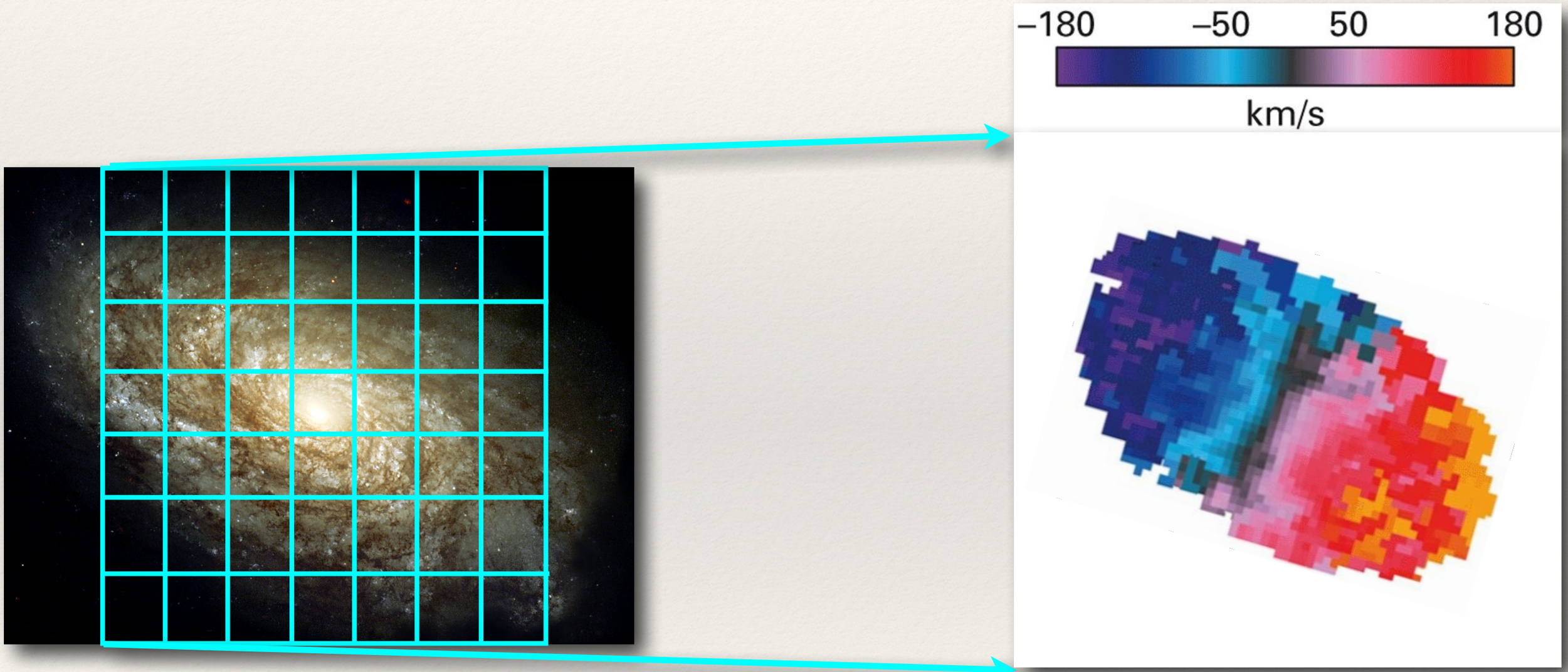


Slit vs Integral field

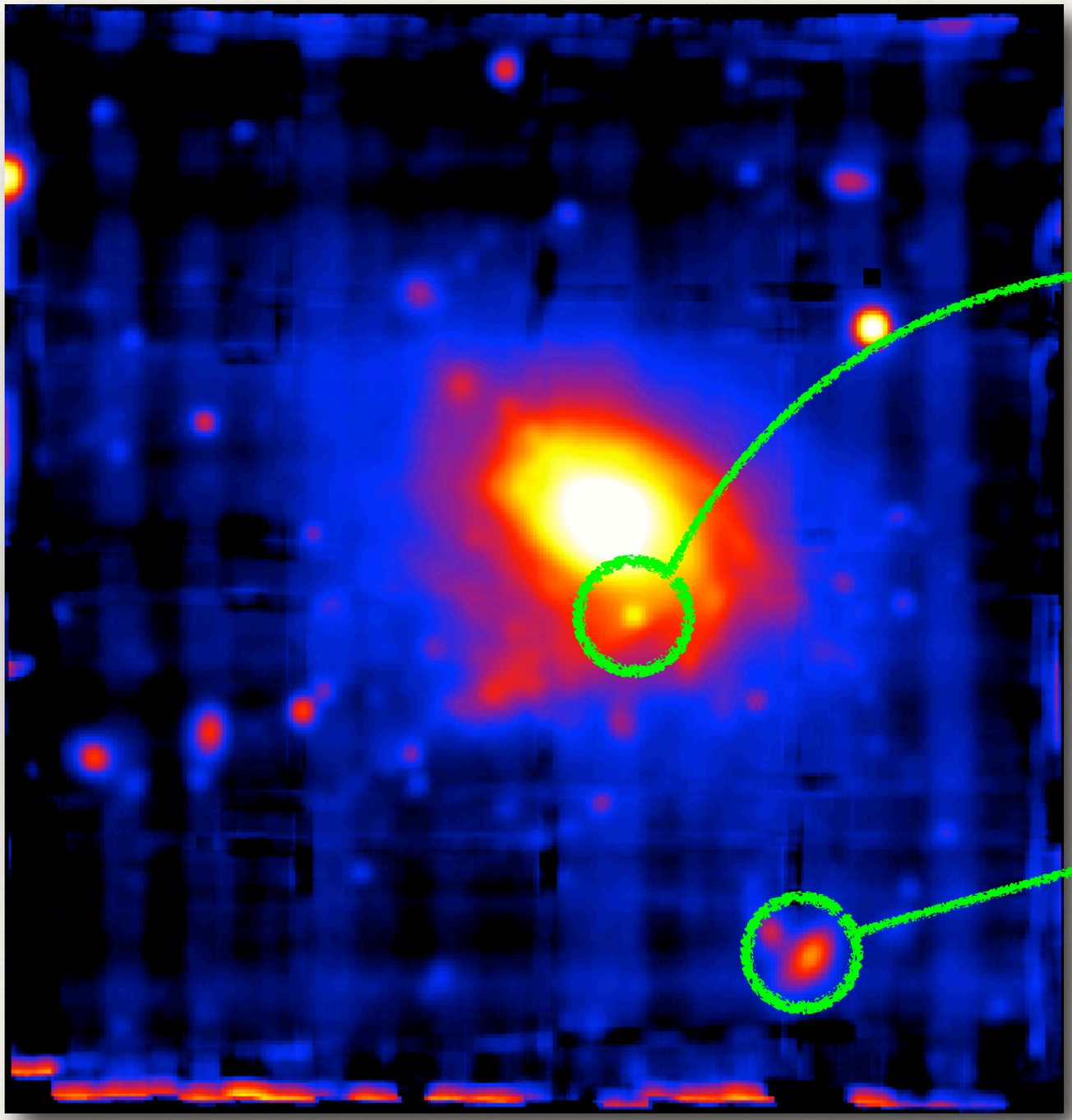
Slit spectroscopy

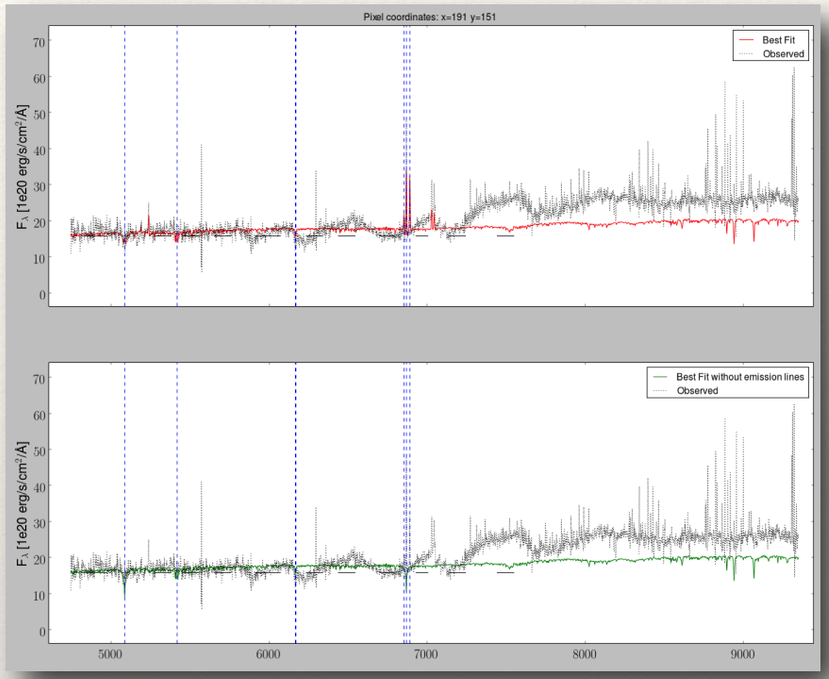
- Limited to one stripe;
- most of the time yields only one (integrated) spectrum;
- ✓ relatively simple instruments;
- ✓ relatively easy data reduction;
- ✓ not so long exposure times.

IFU spectroscopy

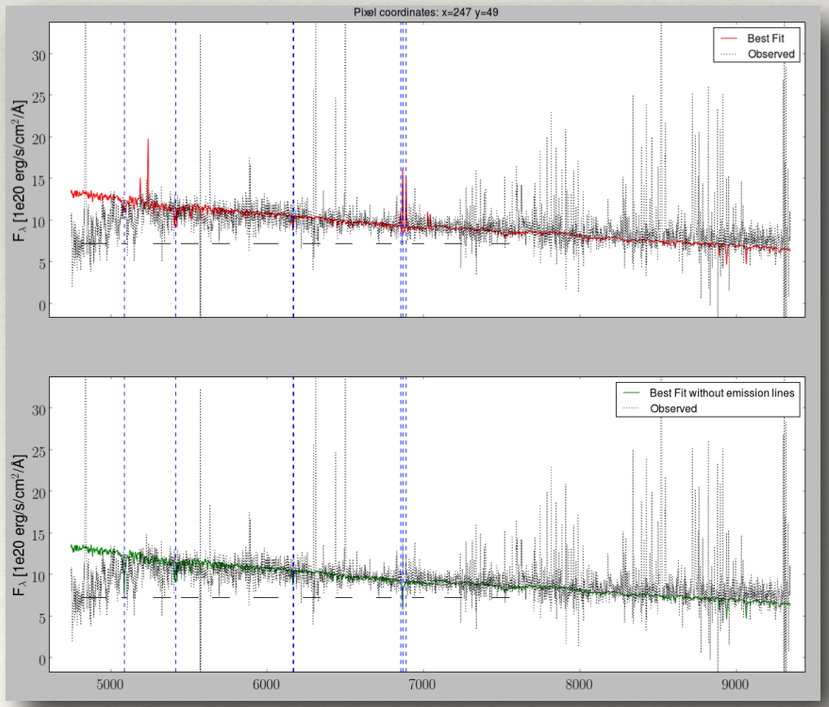
- ✓ Can observe a whole object in one go (or a large part of it);
- ✓ gives one image at several wavelengths;
- ✓ can be used to study the properties of an object as a function of its position;
- ✓ can be used to separate different objects along the line of sight;
- reduction can be a pain.

Deblending example





Foreground star



Background galaxy (z~0.299)

Instrumentation

An IFU is basically composed by two elements:

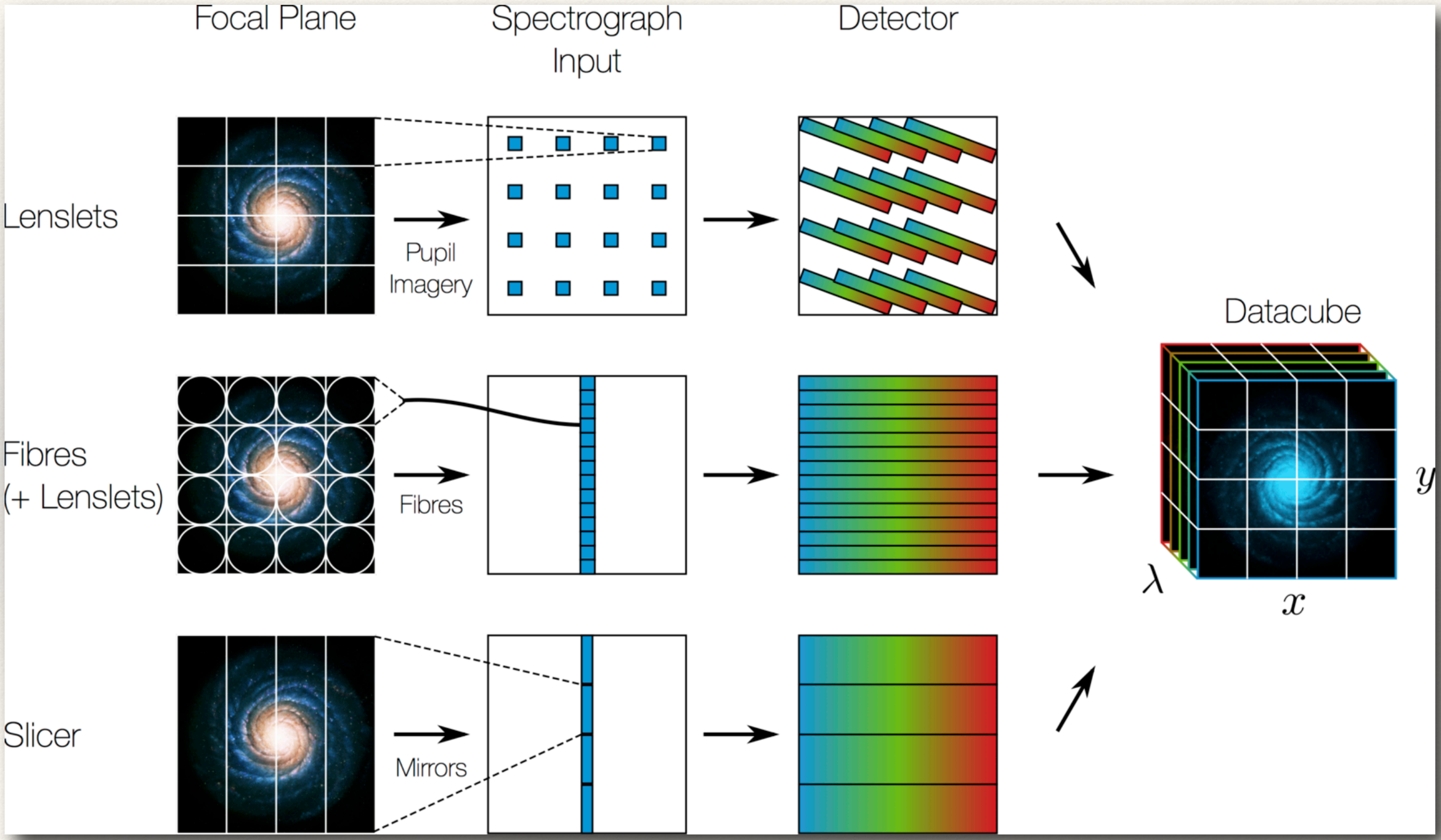
1. An integral field unit → Samples the incoming image in a sequence of consecutive blocks of data that define the spatial coordinates of the single points
2. A spectrograph → Separates the wavelengths

Instrumentation

There are 3 basic types of IFUs

1. Lenslet array;
2. Fiber IFU (with or without lenslet);
3. Slicer.

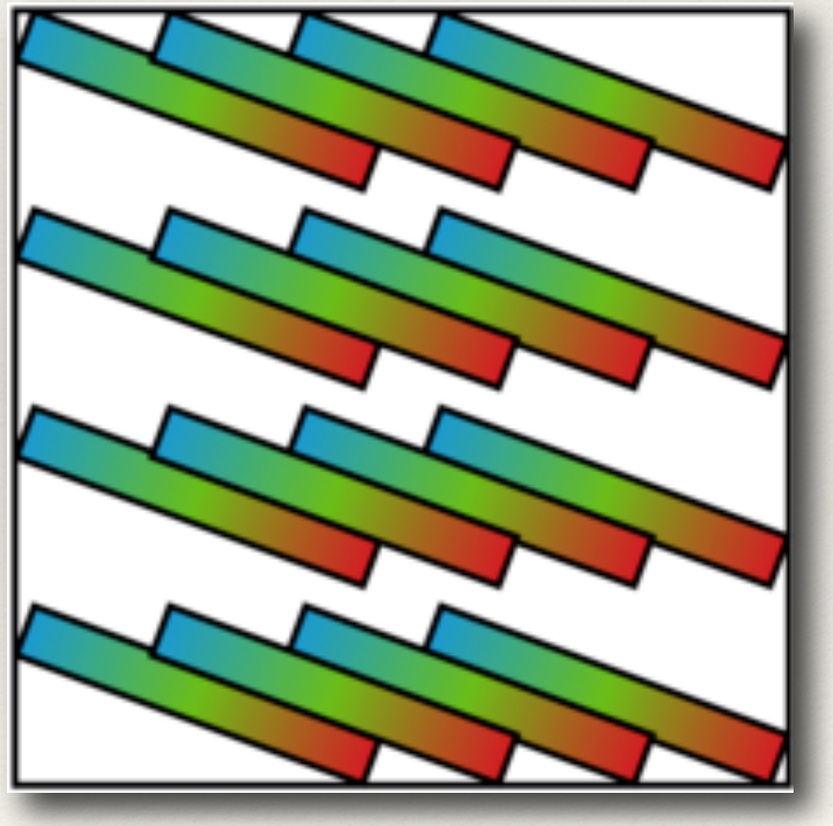
Instrumentation



Lenslet array

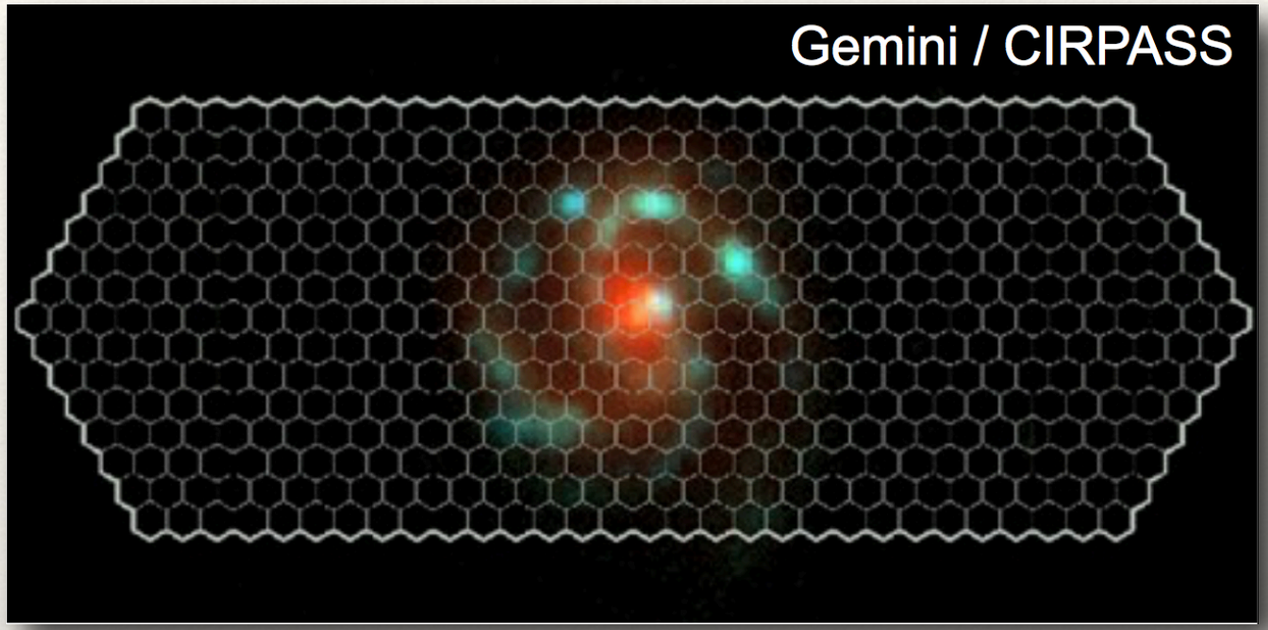
Pros & Cons

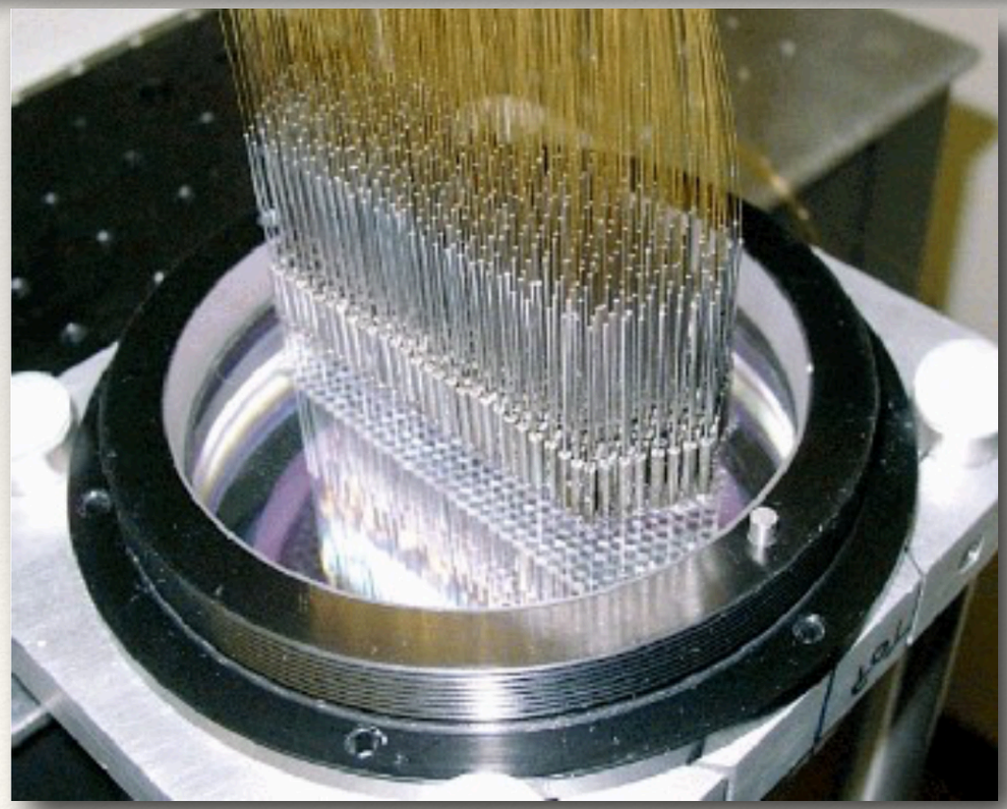
- ✓ Simple by construction
- ✓ Efficient (high throughput);
- ● Inefficient CCD usage;
- ● Short wavelength range sampling.



Lenslet array with fibers

- The focal plane is filled with lenslet, each of which transfers all the light to a fiber;
- the fibers transmit the light to a spectrograph.

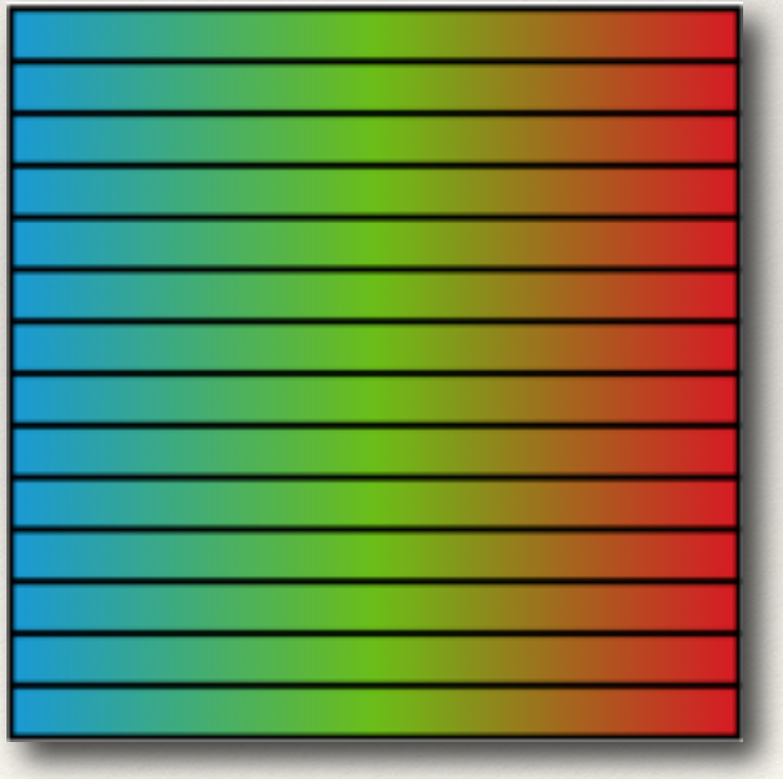




Lenslet array with fibers

Pros & Cons

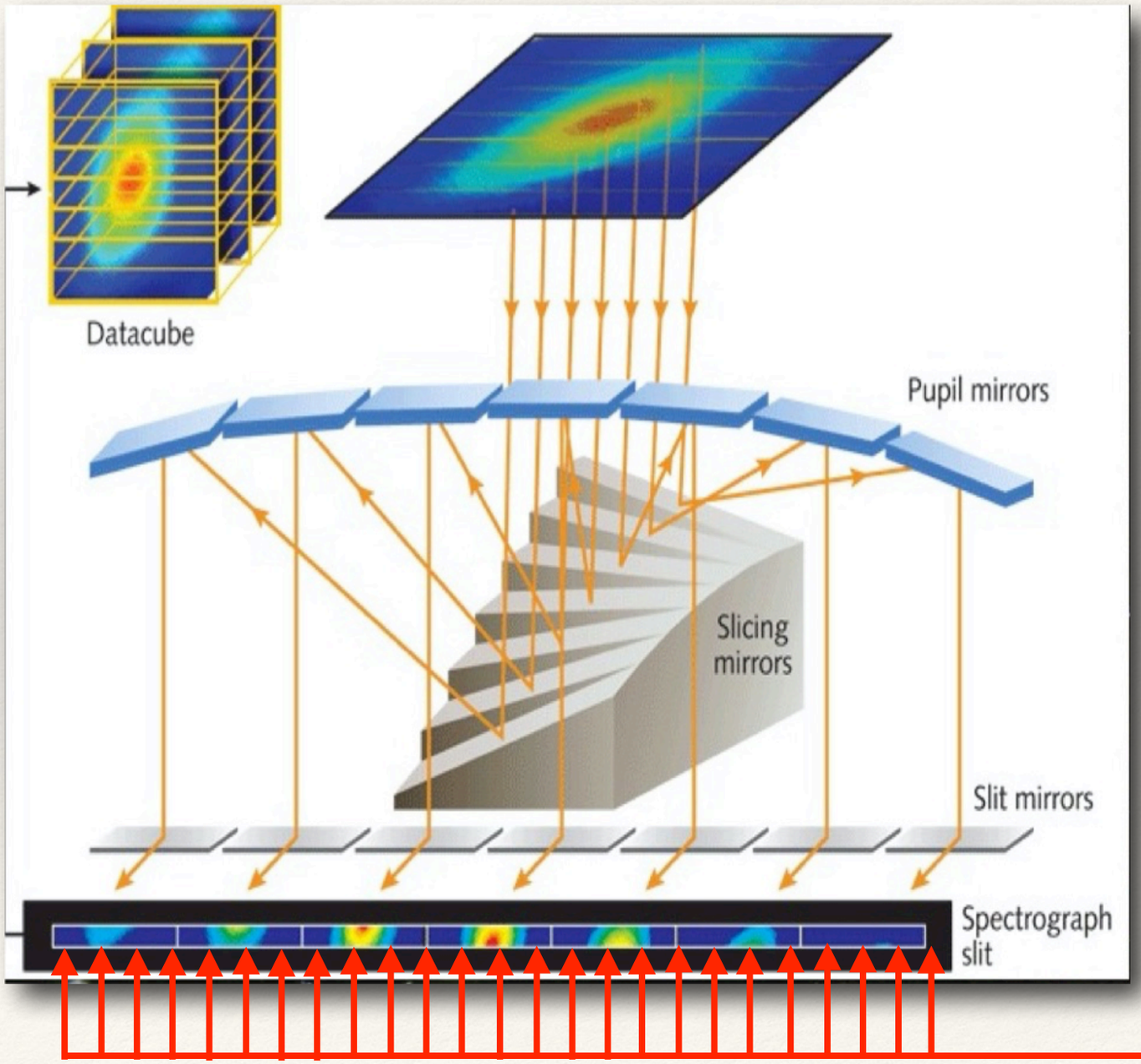
- ✓ CCD fully exploited (and continuously);
- ✓ similar to classic spectroscopy;
- Fiber effects;
- crosstalk on the CCD.



SLICER

- Based on mirror optics;
- the image of the object hits a mirror array that dissects it in slices to send them to different channels;
- each slice is imaged along a row forming a large pseudo slit;
- the dissection in the second dimension happening by the detector pixels similar to a classical long-slit spectrograph.

SLICER



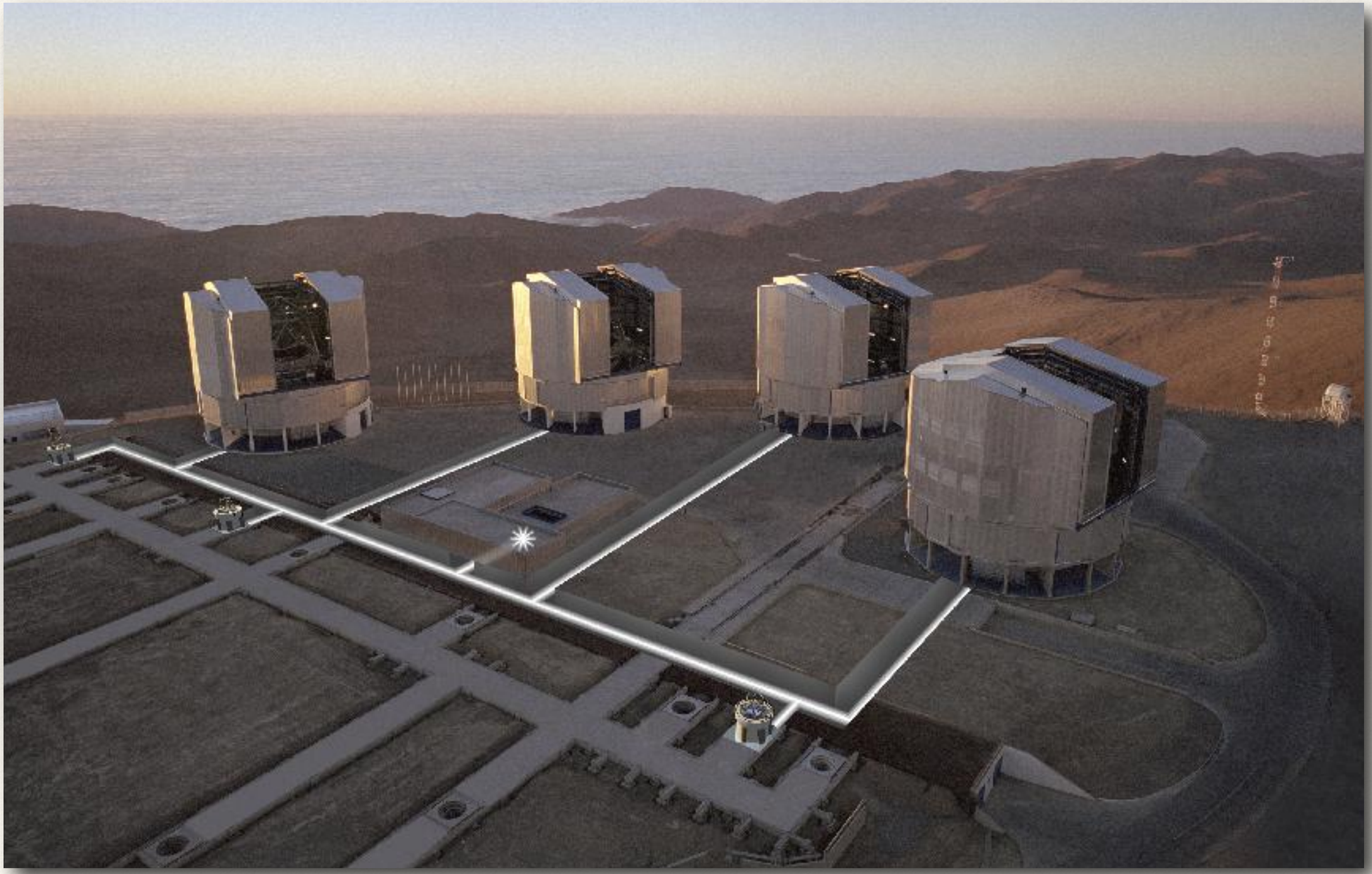
A further spatial division (in spaxels) then happens at this level:

SLICER

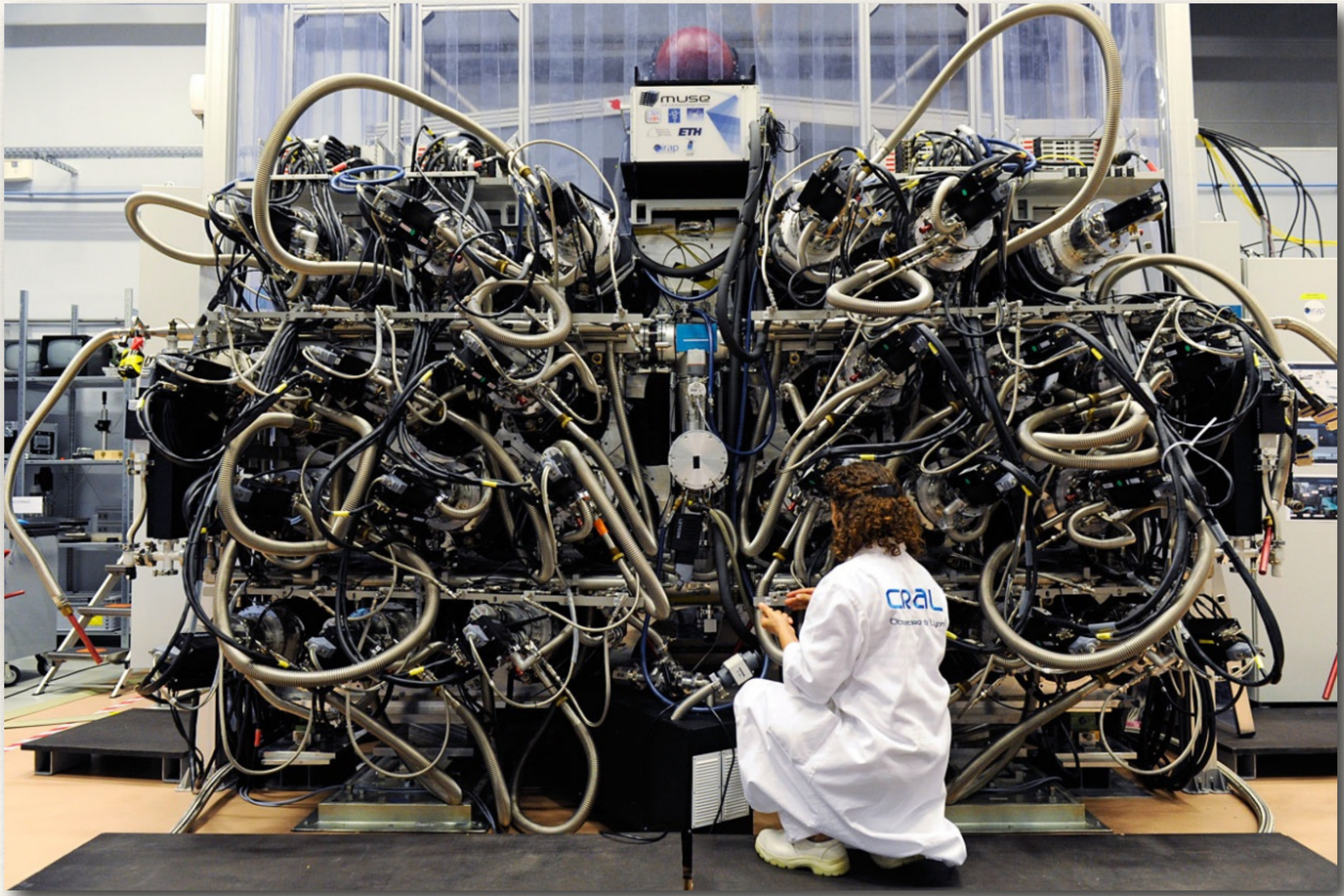
Pros & Cons

- ✓ high throughput;
- ✓ most efficient CCD usage;
- ● Challenging to manufacture.

MUSE@VLT



MUSE



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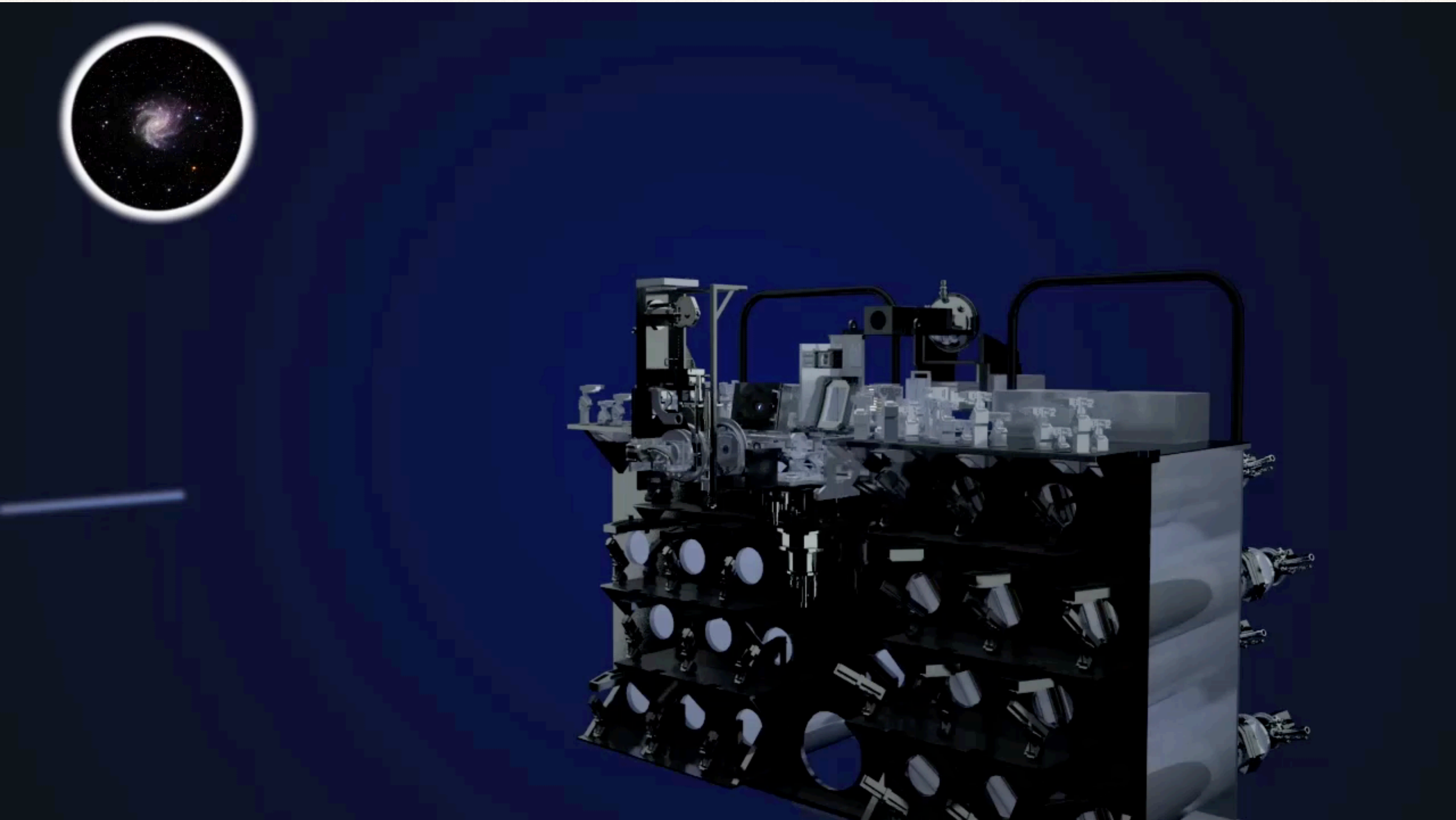
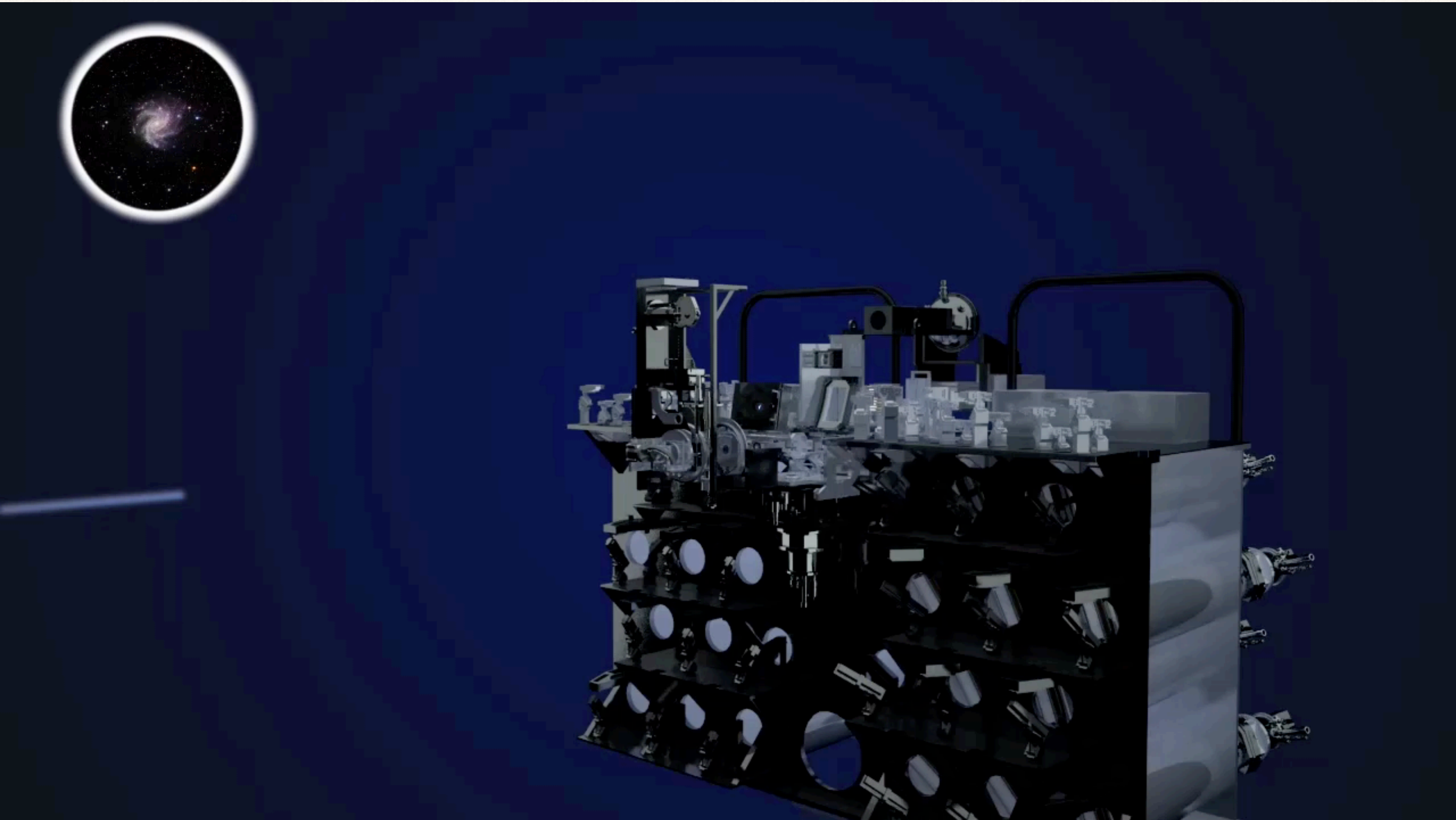


MUSE



More Datacubes

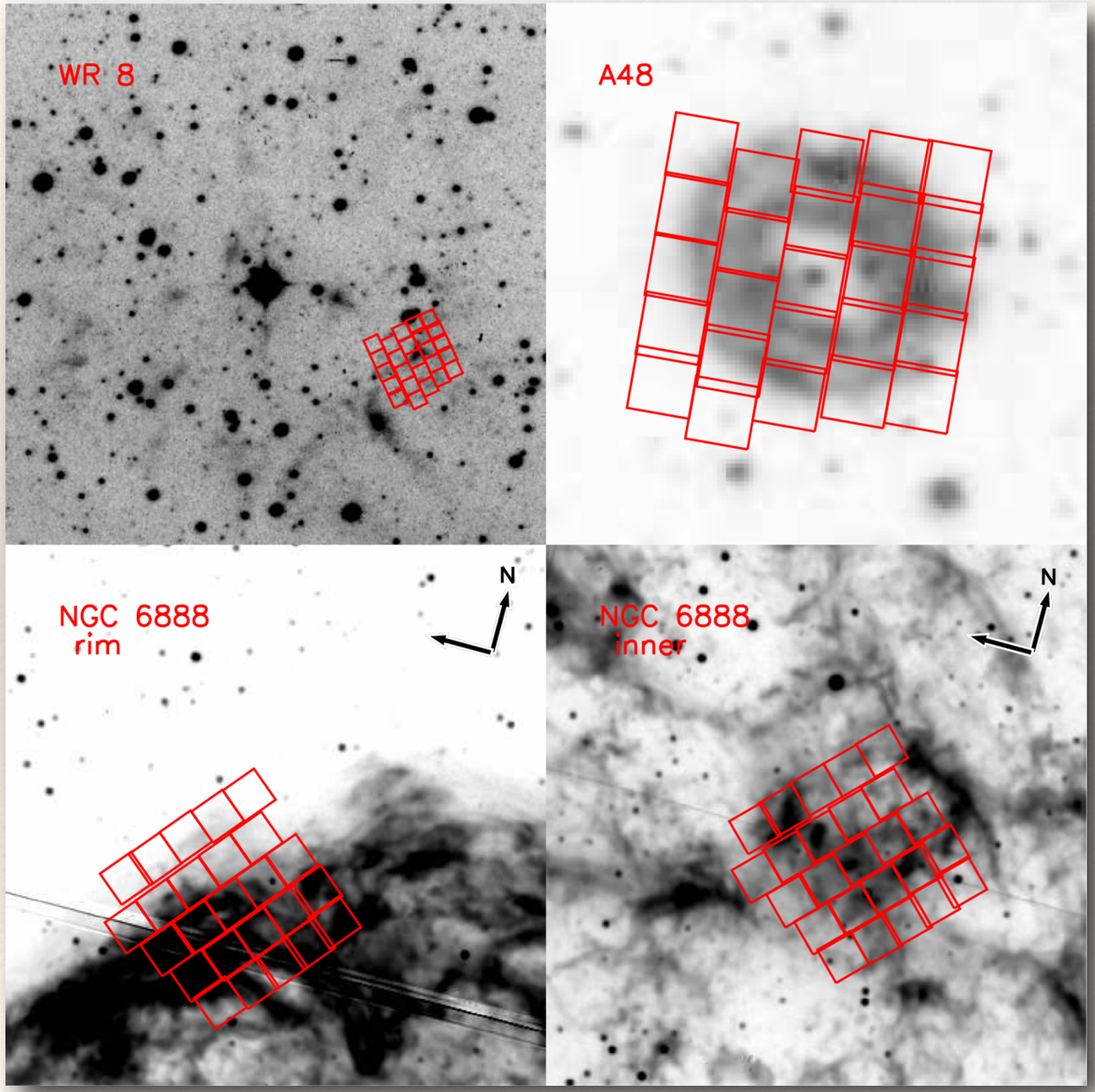
- Optical (classic IF spectroscopy);
- Radio, IR & (sub-)mm;
- X-Ray;
- Theoretical models.

IR: Herschel

- Had three instruments on board:
    1. PACS (photometer + low-res spectrometer ~60 to ~200 μm);
    2. SPIRE (photometer + low-res spectrometer ~190 to ~670 μm);
    3. HIFI (high-res spectrometer ~ 160 to 620 μm).
- PACS and SPIRE were effectively working as IFU!

IR: Herschel

PACS IFU
observing strategy



Stock & Barlow, 2014

Radio and mm

Radio and mm

- Observations can be done with single dishes, or with multiple antennas (interferometry);
- interferometry is used to increase the spatial resolution;
- but it washes away the extended emission component;
- what a detector measures is a temperature variation (Antenna Temperature T_A).

Radio & sub-mm data

- Imaging a single spectral line component at various frequencies (i.e. different velocities)
- …or more spectral lines emitted at different frequencies;
- usually obtained with mapping techniques (various positions or scanning).

Radio & sub-mm data

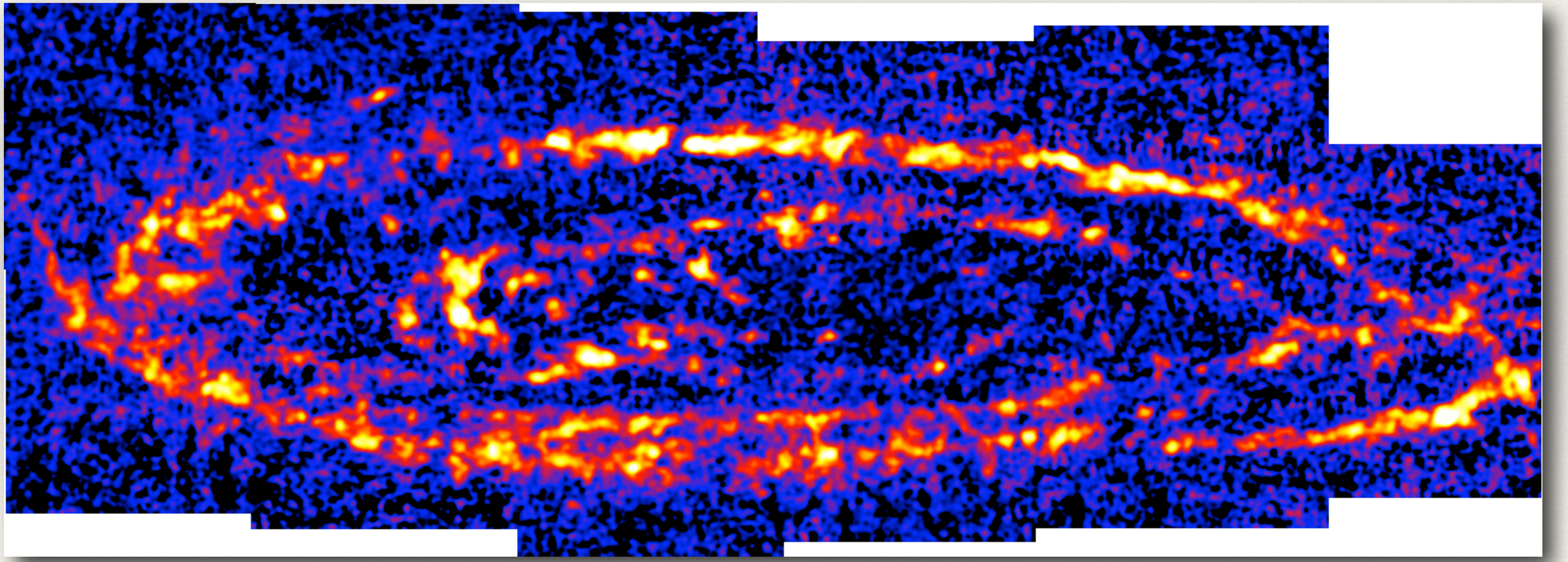
Moment maps

Moments are a way to reduce the size of a large data set into few key numbers.
A *moment map* is when you repeat that process for every pixel of an image.

- 0th-moment: shows the intensity of a line;
- 1st-moment: shows its displacement with respect to the rest-frame (this is, hence, a velocity map);
- 2nd-moment: shows the velocity dispersion of the gas (i.e. basically its temperature).

Radio & sub-mm data

M31 CO 1-0 emission map



Units in K km/s

What can we learn (1 object)

Spatially-resolved quantities

- Stellar dynamics;
- gas dynamics;
- star formation rates;
- dust extinction;
- gas column density;
- ionized, atomic, molecular gas masses;
- stellar population properties (…);
- ionisation mechanisms;
- gas density and temperature;
- stellar and gas metallicity.

What can we learn (MOS)

Multiple objects

- Stellar mass;
- stellar population properties;
- star formation rate;
- dust extinction;
- distance (through redshift);
- metallicity
- cluster membership.

…all in one go!

Summary

- Course presentation;
- slit vs integral field spectroscopy;
- how does spectroscopy work?
- IFU terminology, characteristics, and use;
- IFU instruments;
- X-ray, radio, mm, and IR datacubes;
- the physics to be learnt.