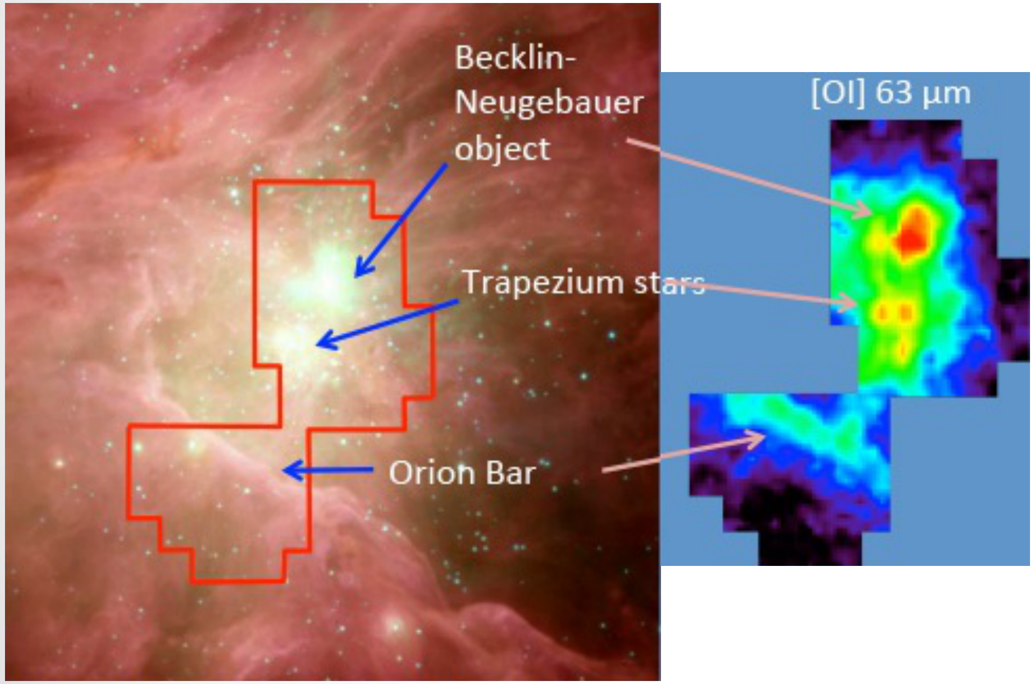
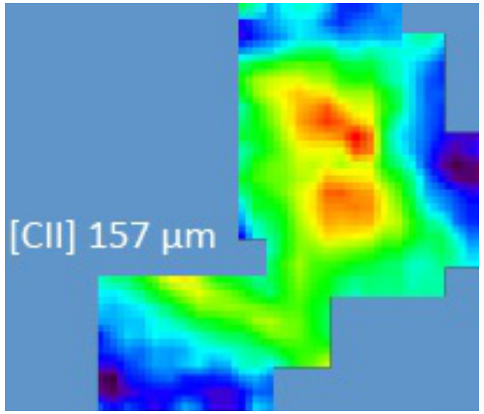
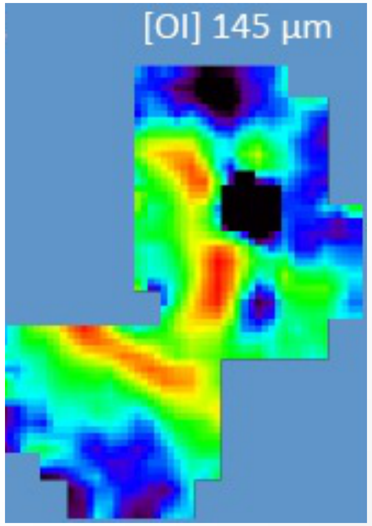
Integral Field Spectroscopy with FIFI-LS







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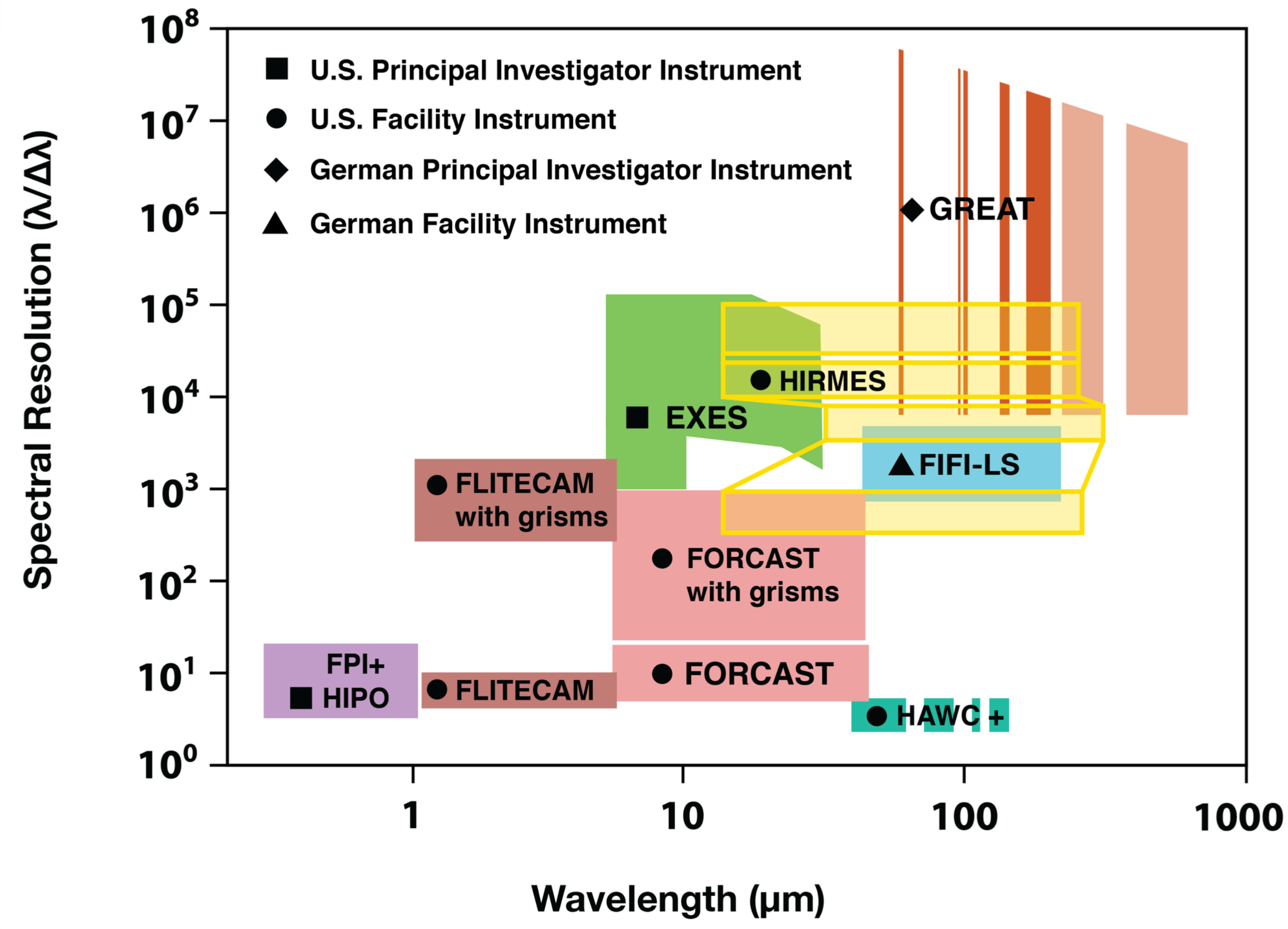
Far Infrared Field-Imaging Line Spectrometer



FIFI-LS covers the mid- to far-IR range in medium resolution

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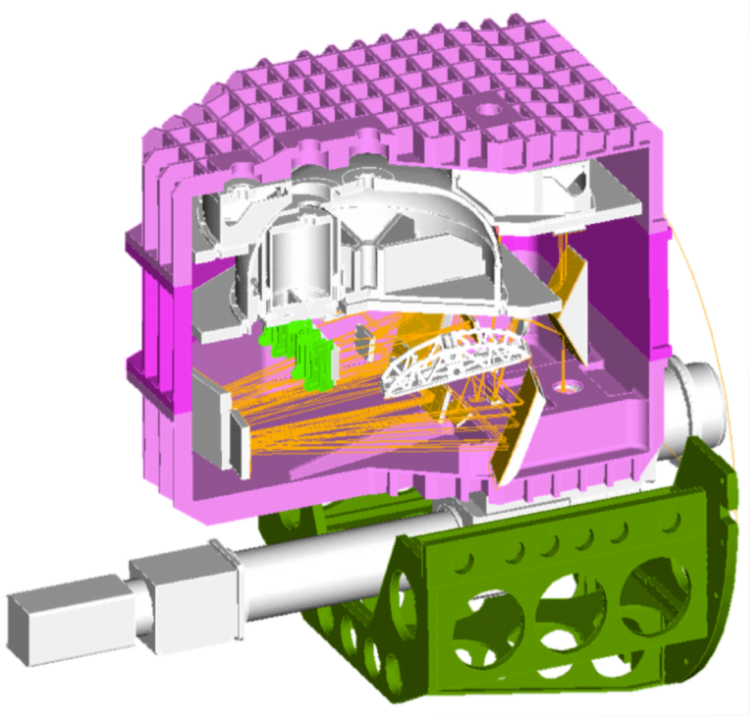
Far Infrared Field-Imaging Line Spectrometer

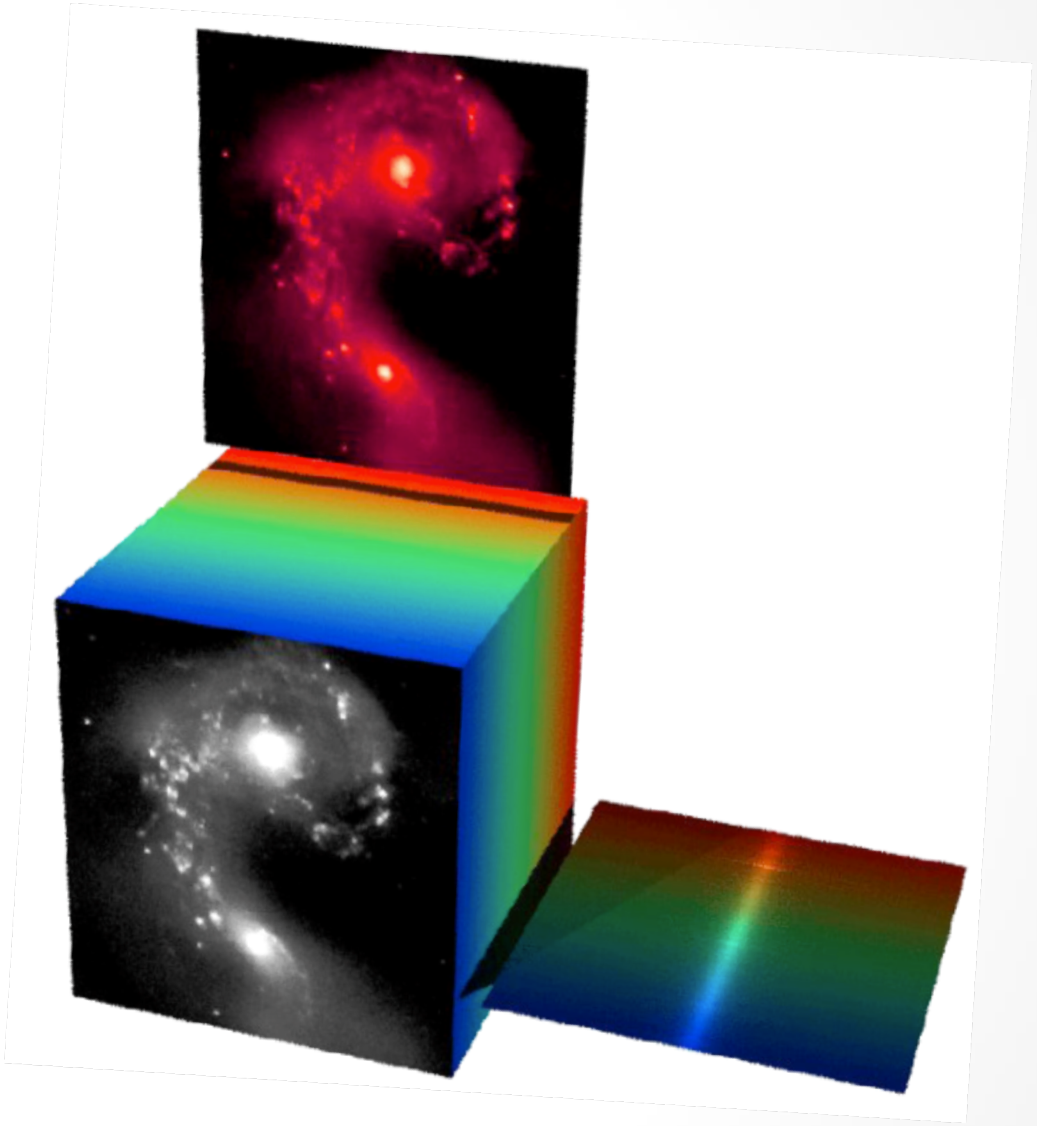
- Far-infrared spectrometer employing two parallel channels operating simultaneously:
  Blue: 51-120 µm, 6" per spatial pixel
  Red: 115-203 µm, 12" per spatial pixel
- Imaging spectrometer concept
- Each channel: 5x5 spatial pixels
- 16 spectral pixels per spatial pixel
- Spectral resolution: R=500-2000



Spectral Cubes

Spectral Mapping results in a 3D-data cube

- P-V diagrams
- Line intensity maps
- Velocity maps



FIFI-LS Science Case

Main Science Application: Mapping of FIR fine structure lines in Galactic and extragalactic sources.

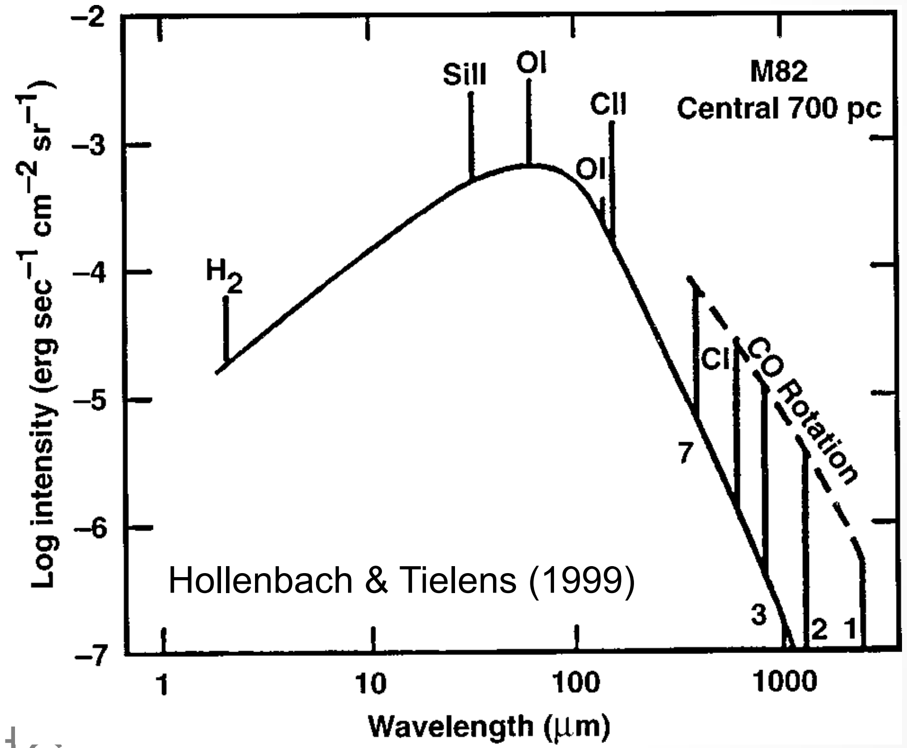
Main cooling lines of the interstellar gas in the FIFI-LS range:

- [CII] 158 µm
- [OI] 63.18 µm
- [OI] 145.4 µm

In ionized regions:

- [OIII] 51.81 µm
- [OIII] 88.36 µm

But also high-J CO lines, OH-lines etc.



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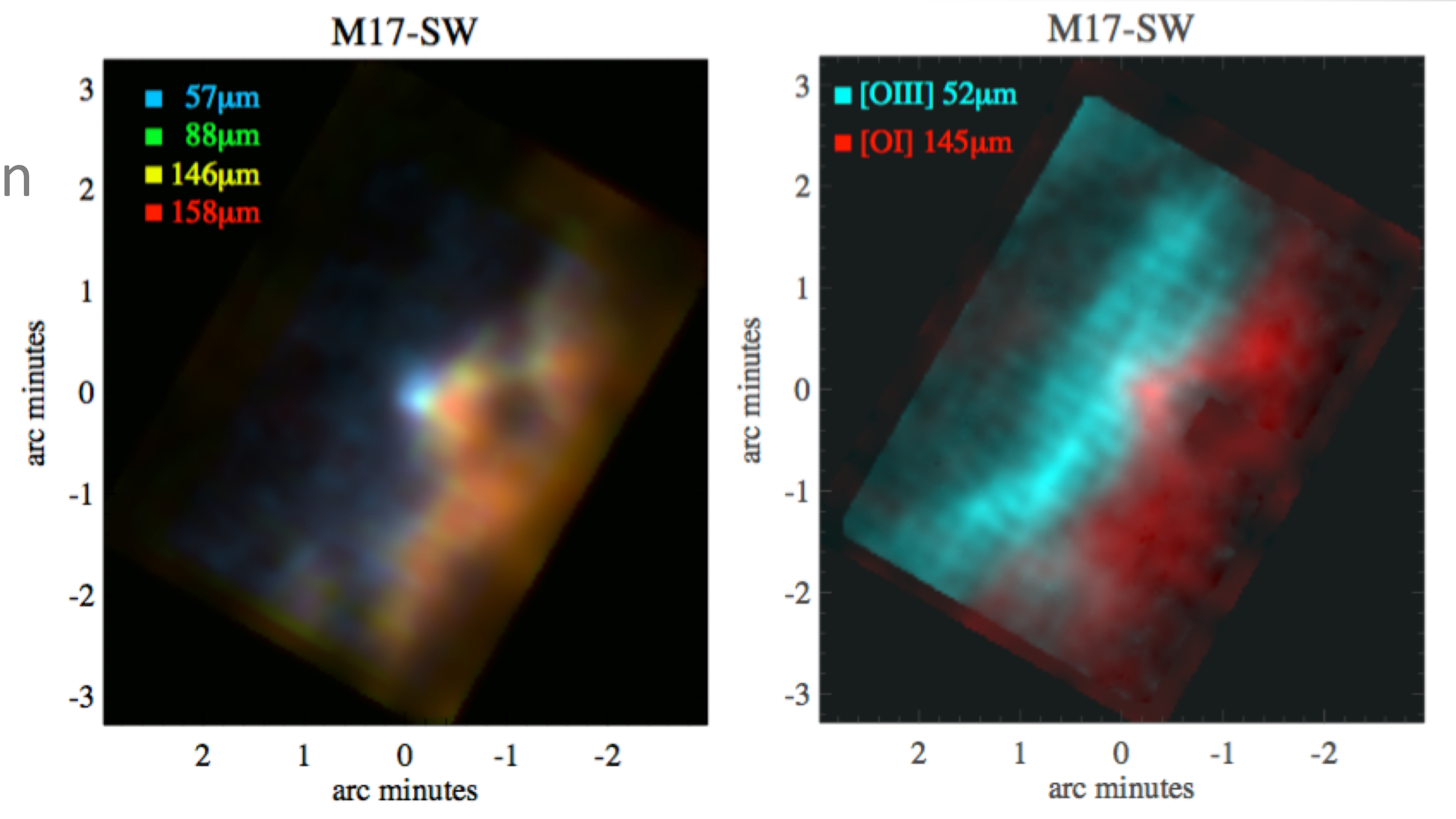
FIFI-LS Science: M17 nebula

M17 is a classic layered photo-dissociation region (PDR) seen nearly edge-on.

- [OI] lines provide density/temperature diagnostic in PDR.
- [OII] lines give density in the HII region.



Continuum and Line Mapping (R. Klein, 2018 in prep.)

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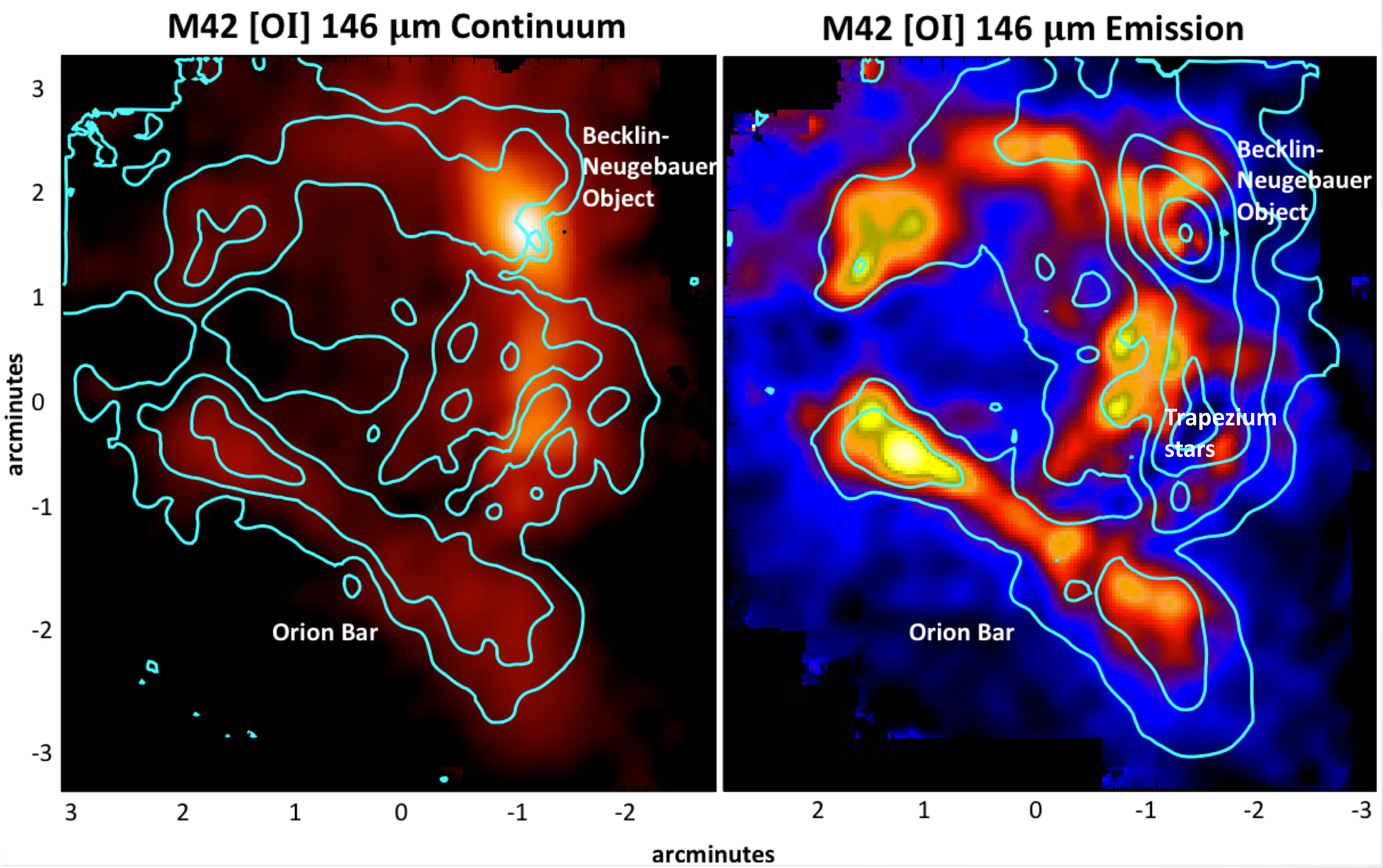
FIFI-LS Science: Orion nebula

The continuum shows the bar and the cloud surrounding the HII region.

The line emission is prominent in the photo—dissociation regions (PDRs).



Colors: continuum
Contours: line emission.

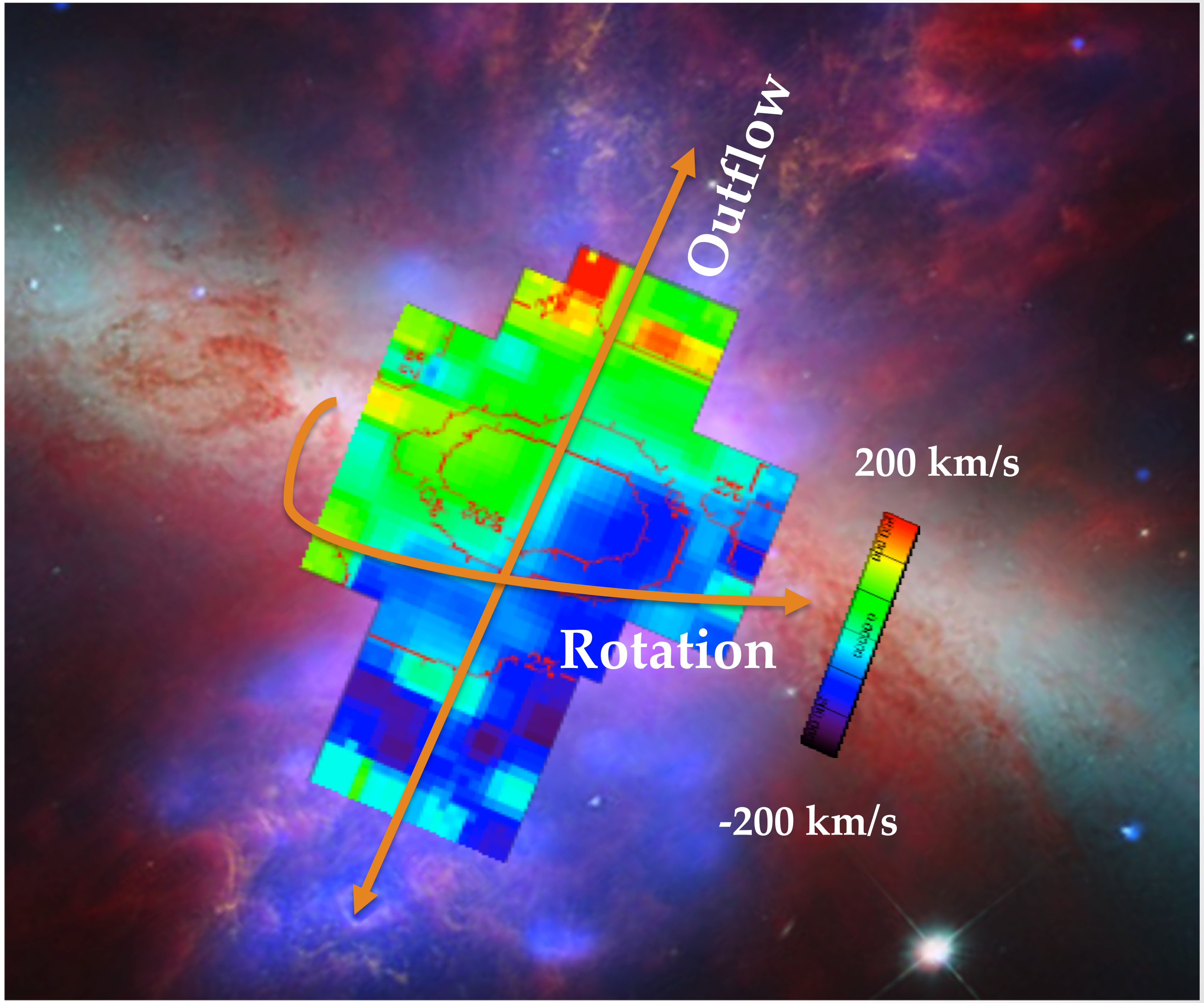
Colors: line emission
Contours: continuum

FIFI-LS Science: M 82 outflow

M82 is an example of outflow important for the study of feedback and evolution of the central black hole.

Herschel observations imply that clouds from the disk are captured by the outflow into the wind. They evaporate into small, dense cloudlets.

FIFI-LS can study the velocity field of the [CII] line.



Ionized carbon at 158 μm

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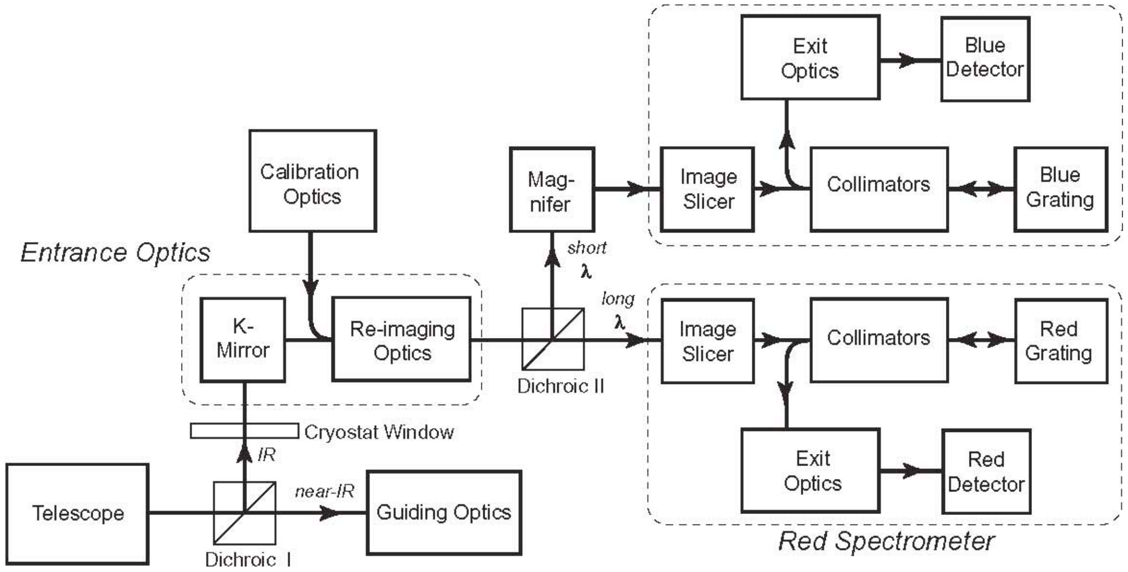
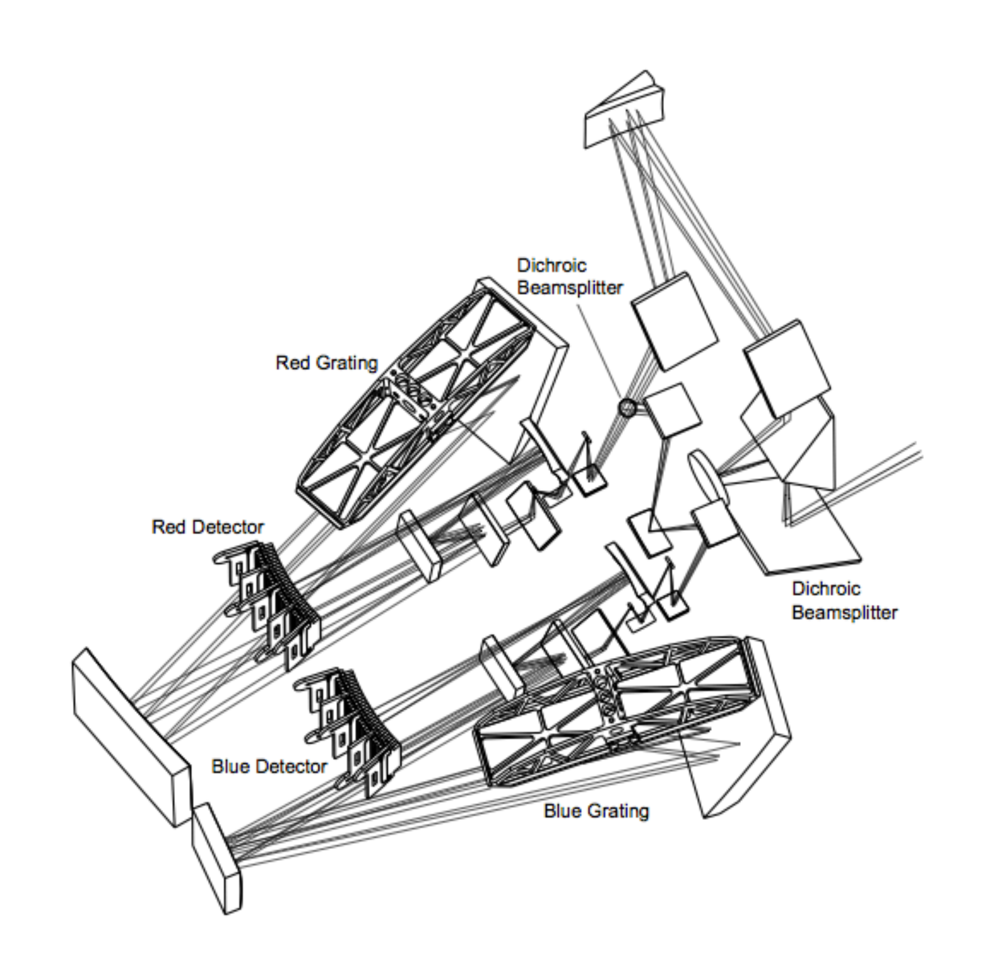
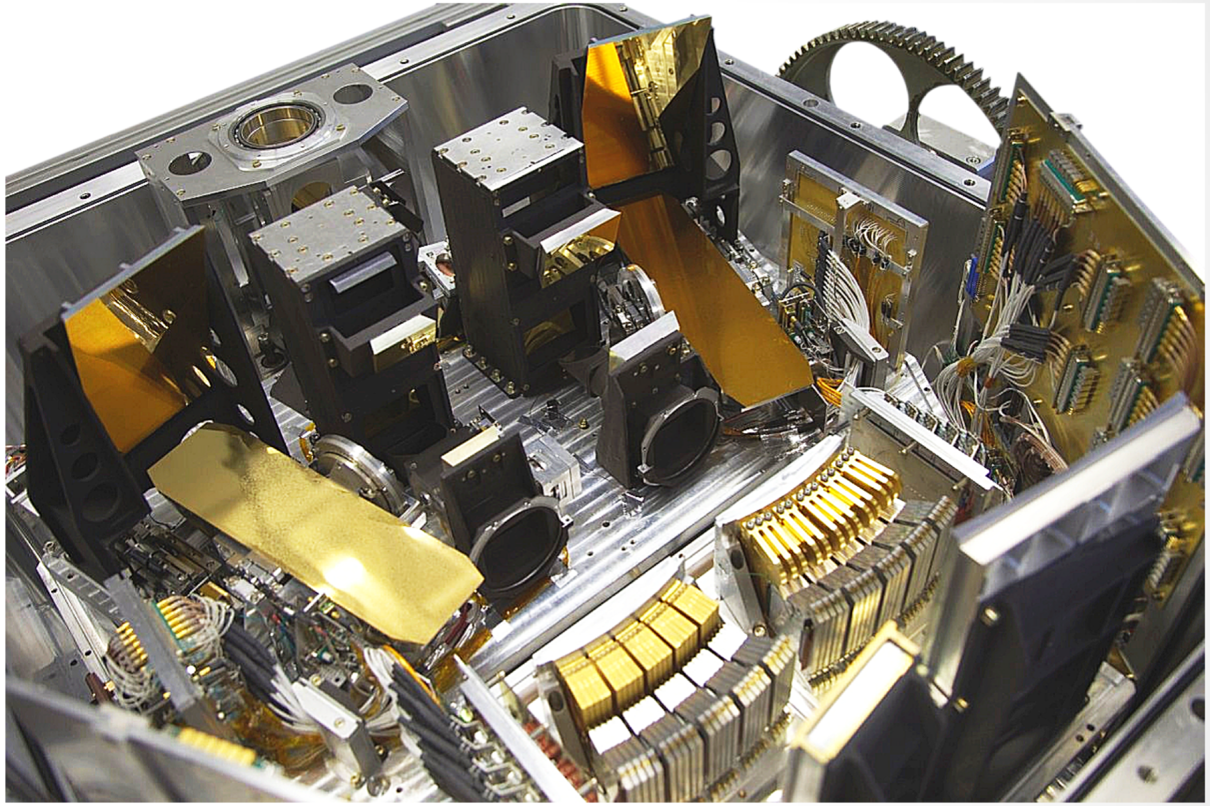
The instrument



- Beam rotator (K-mirror) to counteract the sky rotation
- 2 dichroics to split the light into 2 detectors
- Image slicers to slice the FOV (6"x6" or 12"x12") into 5 slices
- 2 independent gratings to observe two wavelength ranges
- Instantaneous spectra of 16 pixels

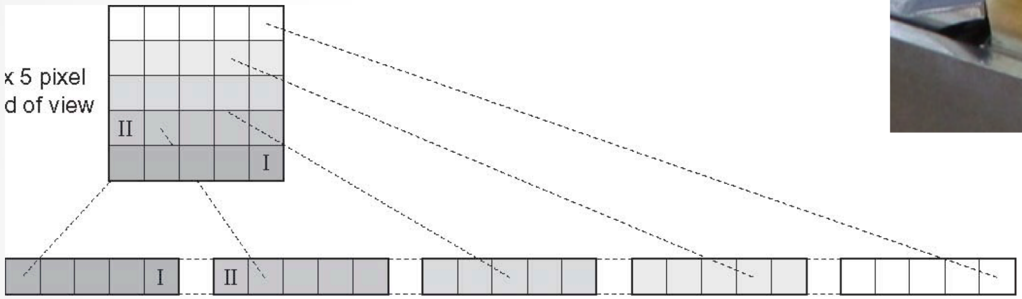
FIFI-LS schema

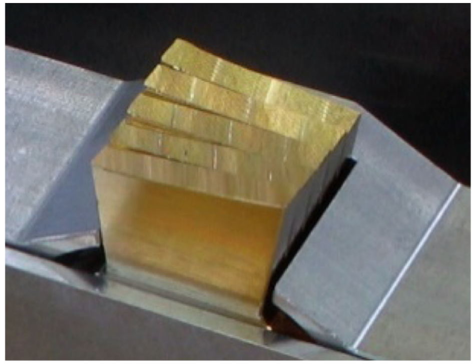


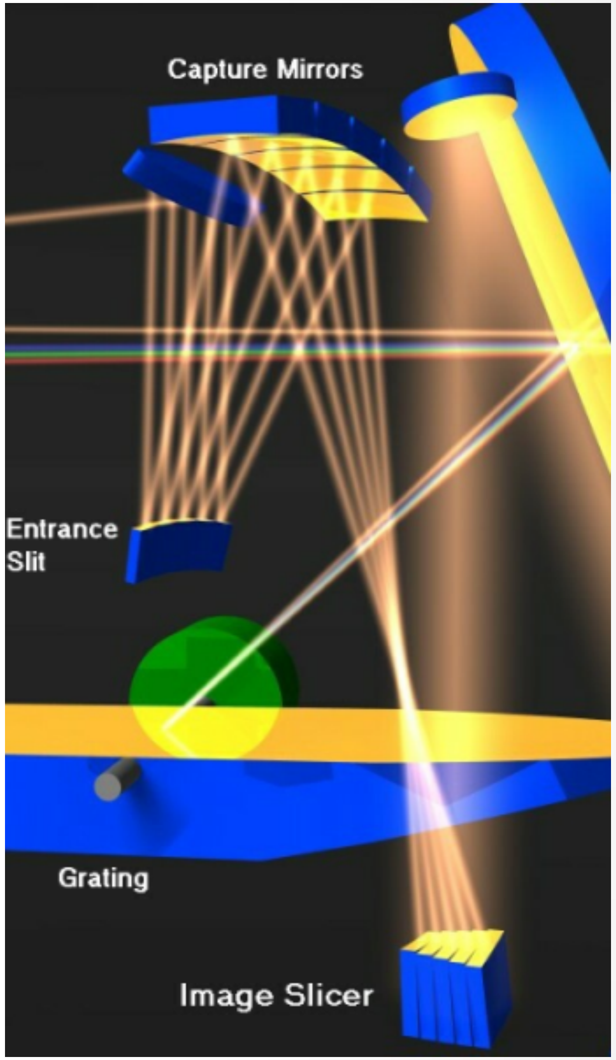


Two independent gratings, two arrays.
Choice of two dichroics (divide at 105 or 130 μm)

Slicers



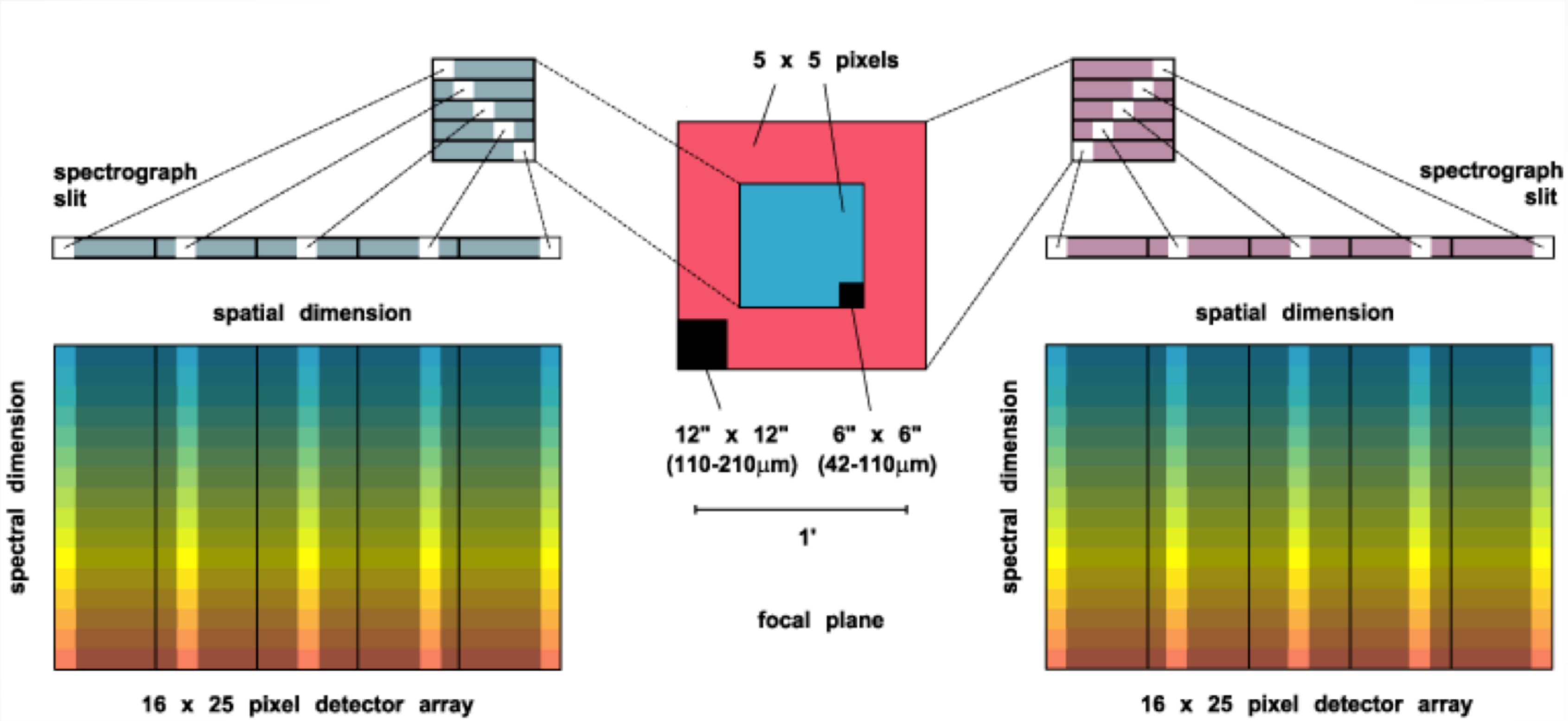




The 5x5 array field of view is sliced in 5 parts.

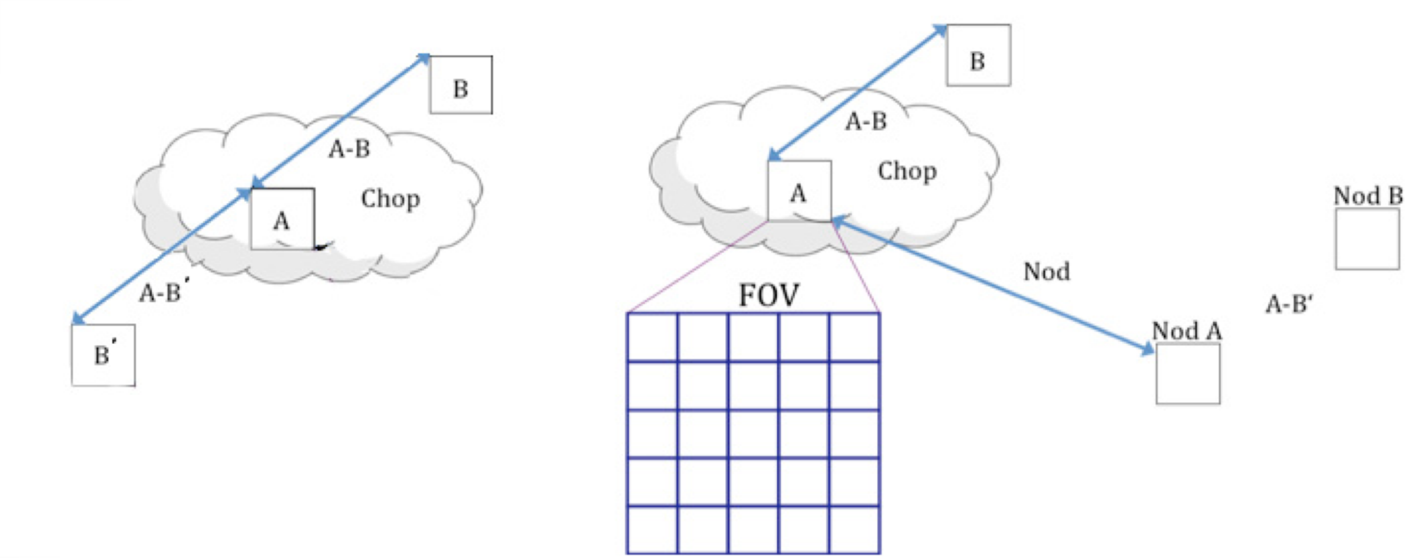
Each one of these spatial modules is then dispersed on an array of 16 spectral pixels.

FIFI-LS data



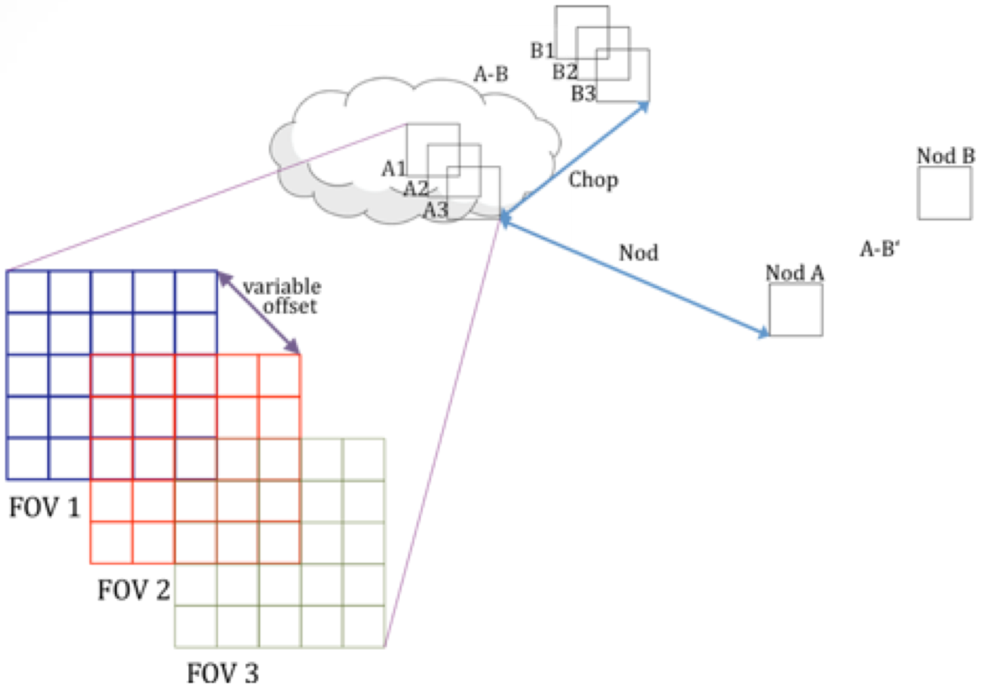
The final data are stored as two 16x25 arrays, one for the blue and one for the red channel. The FOV of the two arrays is different. So, planning the observation of an extended field has to take this into account.

Observational modes



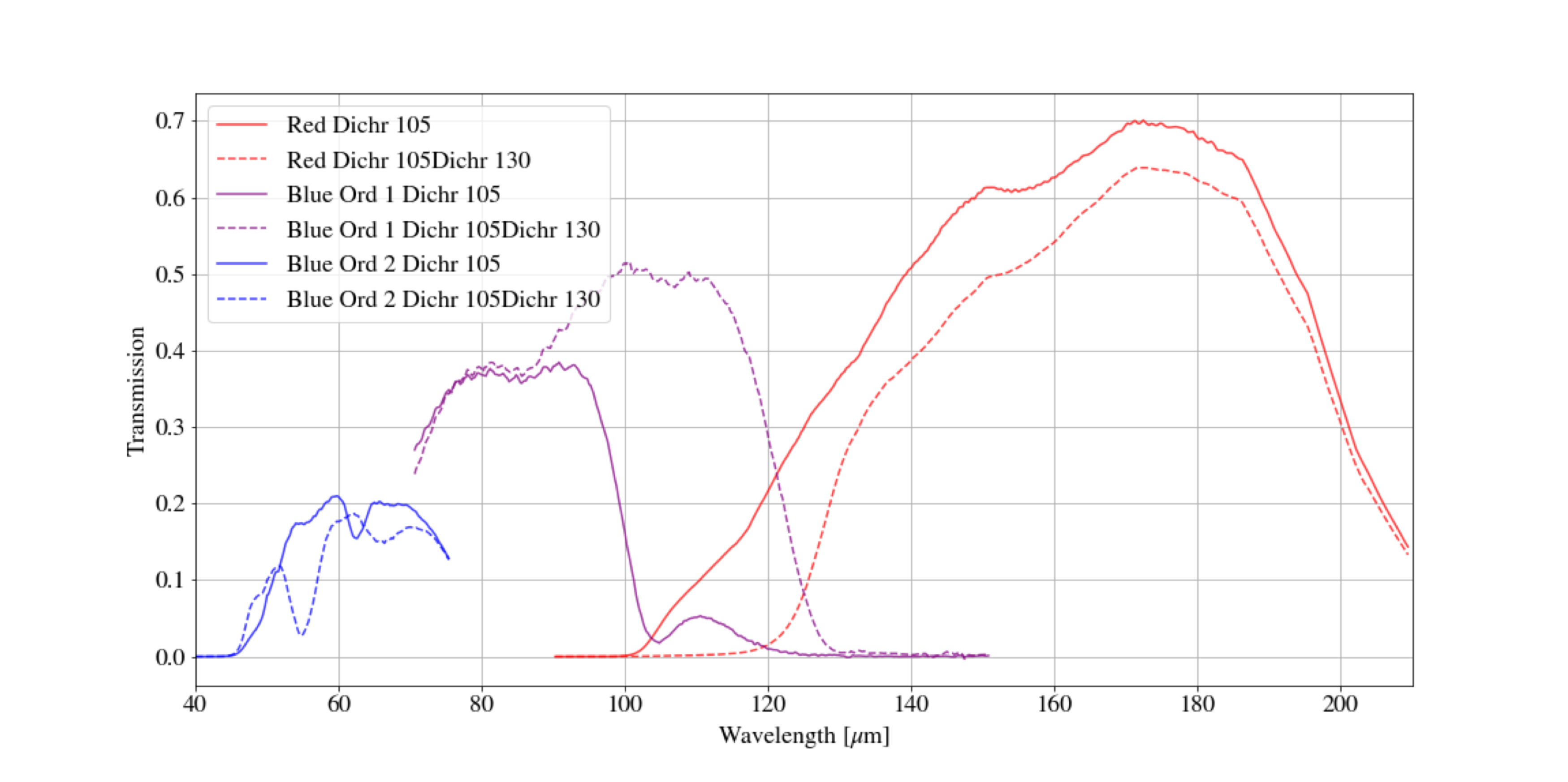
- Symmetric chop:
  - Matched nod → symmetric nod positions
  - Max chop throw 4' for λ< 63 μm and 5' for λ up to 120μm
  - Overhead ~ 170%, assuming long integration times
- Asymmetric chop
  - Needs reference position (can be absolute)
  - Overhead ~ 430%

Special observation modes



- Spectral scan
  - Several grating steps to observe large wavelength range
- Bright object
  - Asymmetric chop with 2 ON position per nod cycle
  - Overhead 500% (assuming on time of 5s)

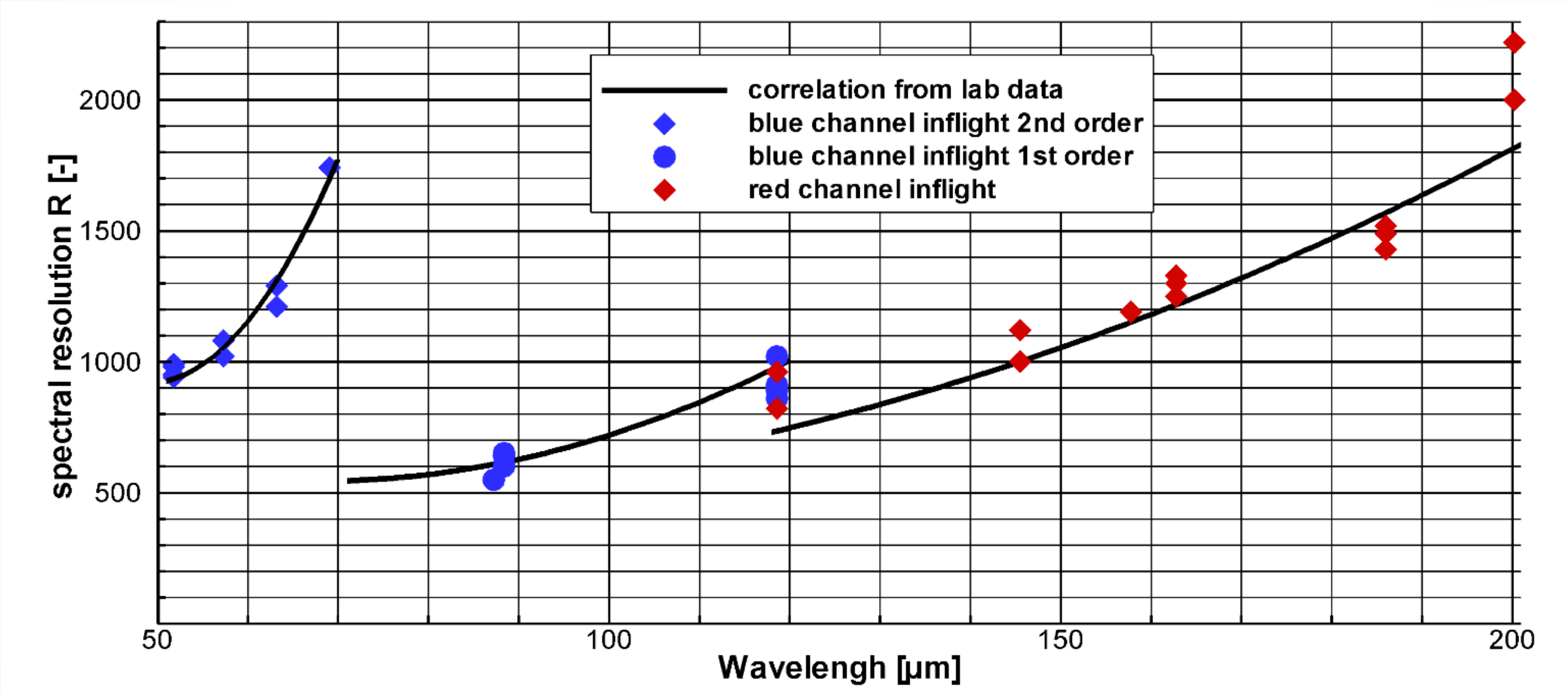
Dichroic selection



It is important to select the correct dichroic to have the maximum sensitivity around the line of interest. Obviously, since two channels are observed at the same time, a compromise has to be made.

Note the extended band at 50μm available in cycle 7 !

Spectral resolution



The spectral resolution ranges between 500 and 2000.
It depends on the order and on the wavelength range.

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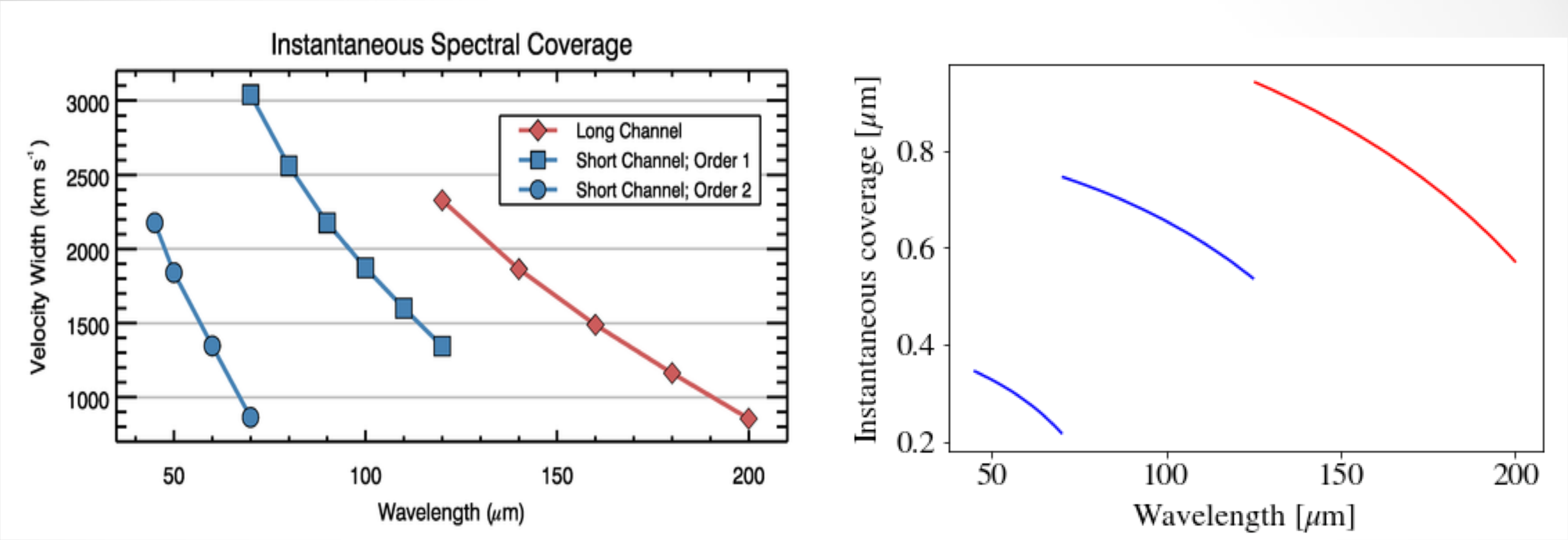
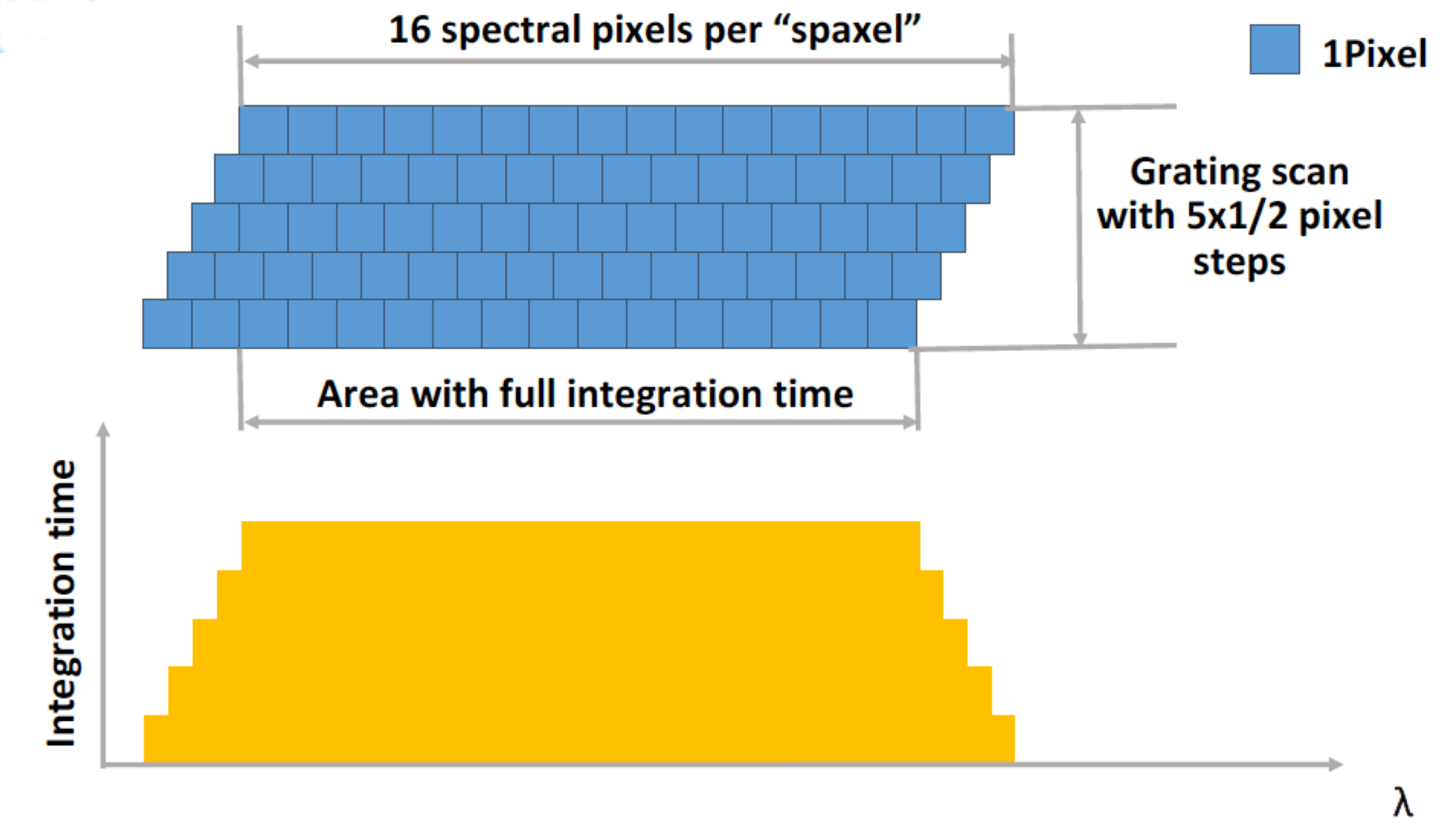
Instantaneous coverage



The instantaneous coverage is usually not enough to contain the line and some continuum. Therefore, a few grating positions are used during the observation. Typically, the grating step corresponds to half the wavelength difference between adjacent pixels.

Spectral coverage



The coverage can be extended by moving the grating.

Typically, a 4 position grating is done to have some spectral dithering.

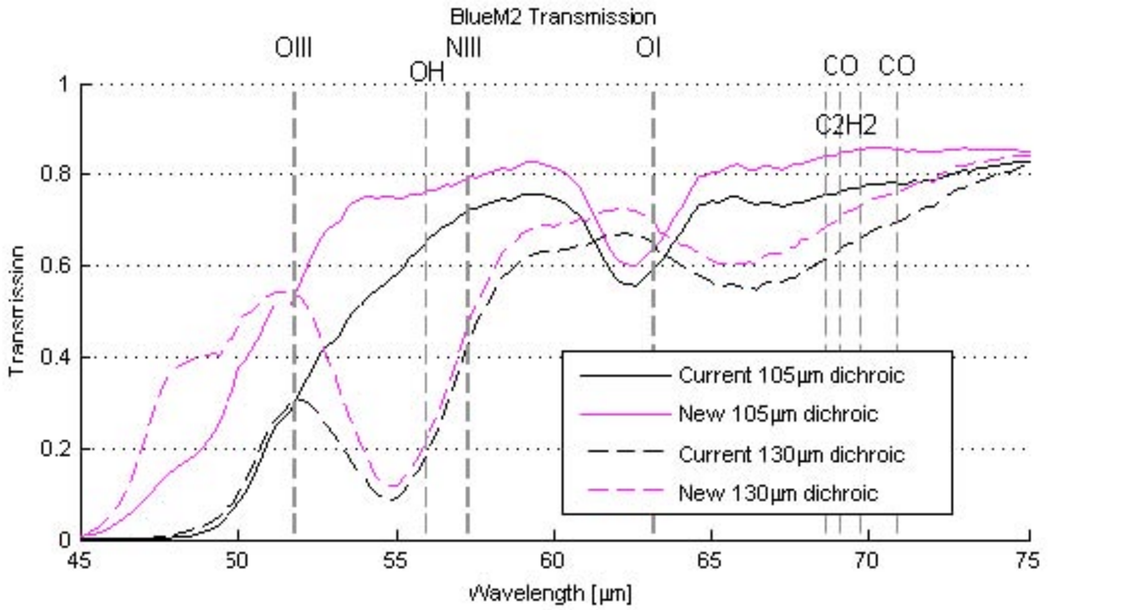
Filter and dichroic upgrades

Upgrades

- Replaced entrance filter
- Added blocking filter for blue channel 1st order
- Replaced filter blue channel 1st order
- Replaced filter blue channel 2nd order (low pass)

Effects

- 77% transmission increase below 53 µm
- Minor transmission losses at 88 and 145 µm
- 10%-20% better transmission at wavelengths longer than 160 µm



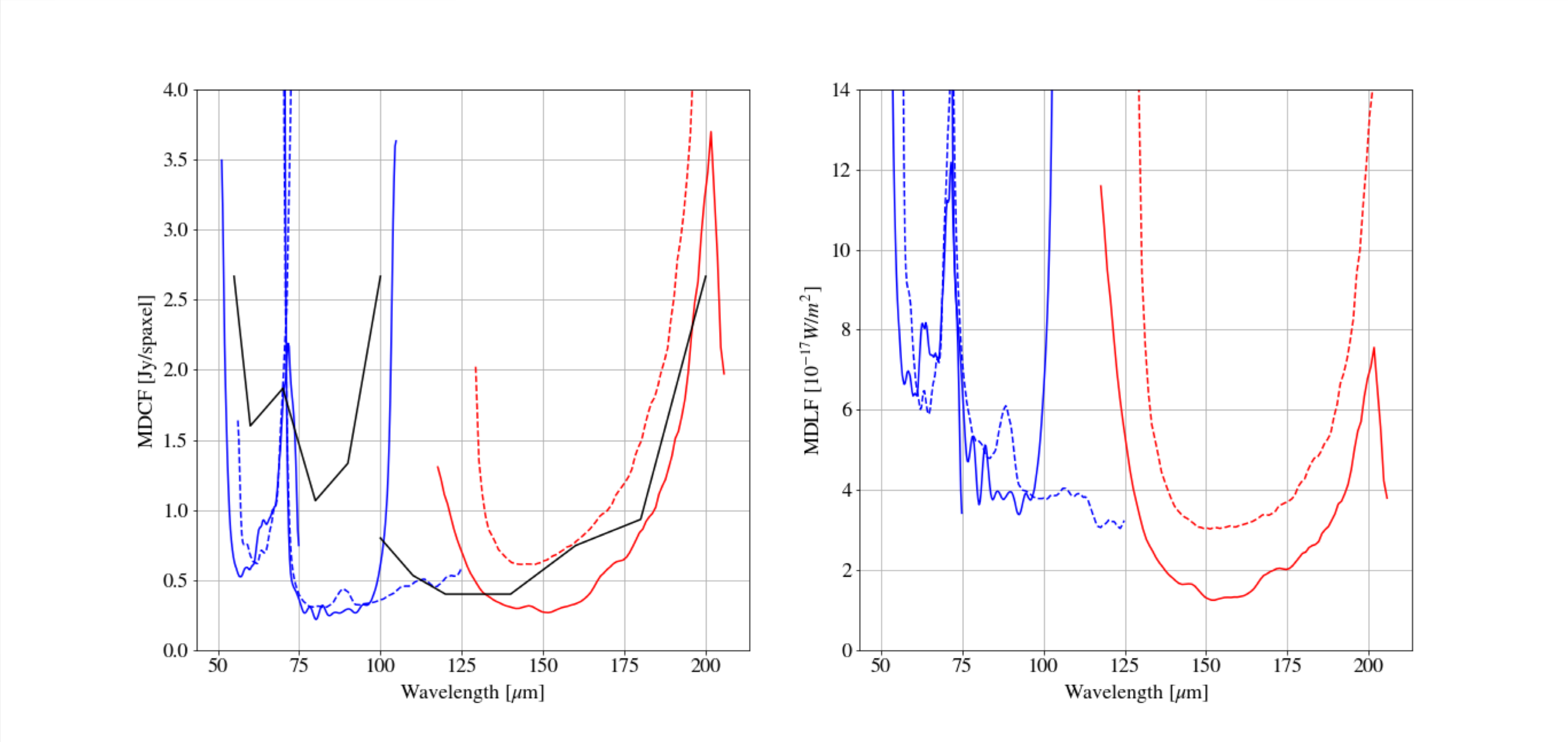
Filter transmission of blue channel 2nd order

The new sensitivity curves have been computed using the internal calibrator and will be used in the new version of the FIFI-LS time estimator (end of May).

Comparison with PACS

- FIFI-LS has two independent gratings for the two channels while PACS had one grating for parallel observations
- Blue and red arrays have different pixel size (6 and 12 arcsec) to better sample the PSF while PACS had a size of 9.7" for the two arrays
- FIFI-LS offers asymmetric chop for large chop throws
- K-mirror enables alignment of objects along slits
- Blue channel starts around 50μm enabling the observation of the [OIII] 52μm line impossible with PACS
- Blue and red channel overlap (105-130μm)
- Telescope can move fast allowing fast slewing during mapping, allowing for more dithering and smoother spatial images.

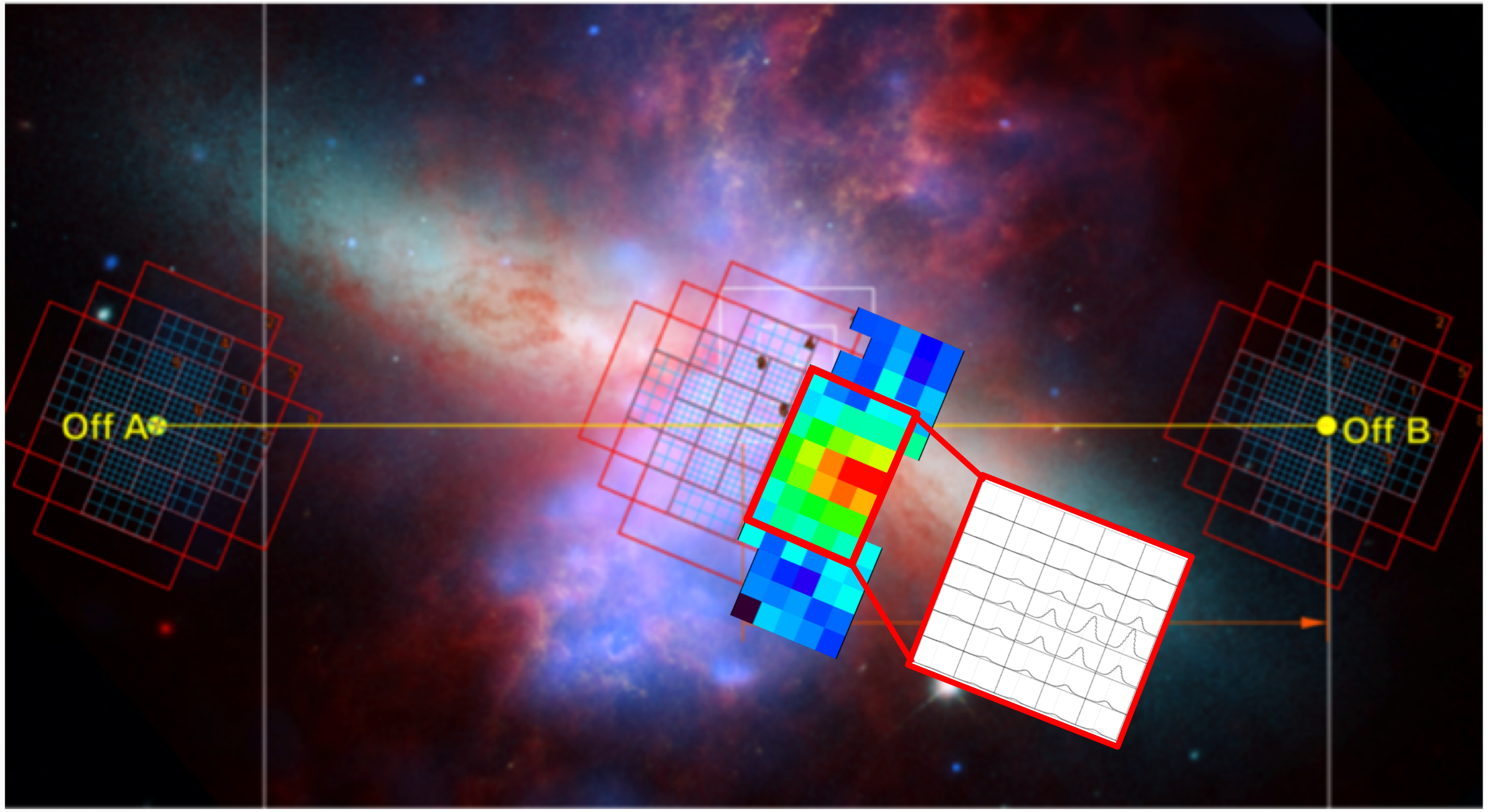
Sensitivity



Minimum detectable continuum flux for an observation of 900s at 4 σ level. FIFI-LS performs better than PACS (black) in the blue thanks to the different pixel size.

Lines below 53μm can be only observed with FIFI-LS. **The new filters installed increased the sensitivity around 50μm by more than 60%.**

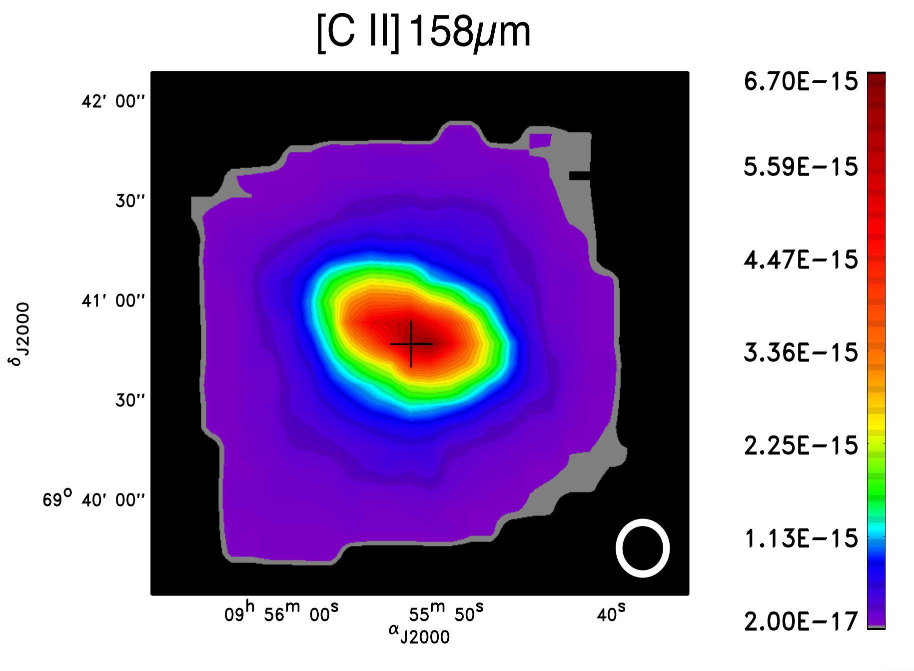
Example: Mapping M82 at 158 μm



Let's plan an observation of M 82

Time estimate from literature

- Expected flux e.g. from KAO, ISO, or Herschel observations
- From Herschel PACS-S: Central 2'x2' with PACS-S
  Contursi et al. A&A 549, A118 (2013)
- Expected integrated line flux for [CII]:
  ~2x10^{-17} W/m^2 *per PACS-S spaxel in outer regions*
- PACS-S spaxel is 9.7"x9.7"
- FIFI-LS red spaxel:
  12"x12" -> 1.5 times larger
- Expected flux per FIFI-LS spaxel: 3x10^{-17} W/m^2



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FIFI-LS time estimator

Input Parameters

Observatory Altitude (in feet; < 60000 ft):	38000	◉ft ○m
Water Vapor Overburden (in microns; 0 if unknown):	0	
Telescope elevation (between 20 and 60 deg):	40	
Signal to Noise Ratio / Integration Time (minutes):	5	◉SNR ○ On-Source Int. Time
Wavelength (in microns, between 51 and 205):	157.741	
Source Flux:	3e-17	◉line (W/m^2) ○ continuum (Jy)
Source Velocity (in km/s):	219	
◉ **Input Observer Velocity** (VLSR in km/s):	0	- OR - ○ **Enter UT Date:** 2018/03/10 **UT Time:** 12:00:00 **Source RA:** 09:55:54.20 **Source Dec:** +69:40:59.53 **Location:** Palmdale
Band width :	1500	◉km/s ○microns
Comment :	M82 example	

Input values in the FIFI-LS time estimator:

https://atran.sofia.usra.edu/cgi-bin/fifi-ls/fifi.cgi

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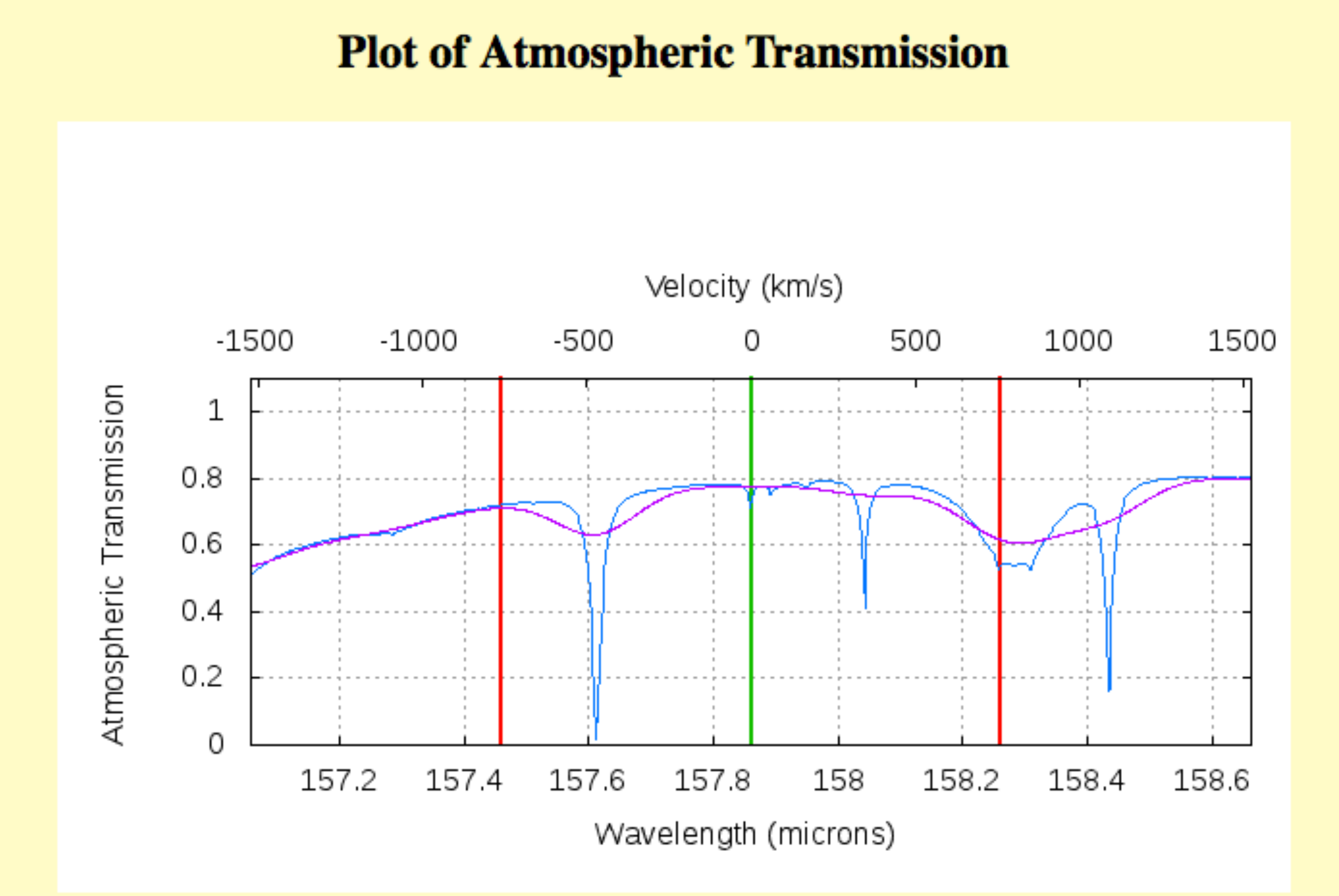
Inspecting atmospheric transmission



Consider band width and effect of the atmospheric transmission (given unsmoothed and convolved with FIFI-LS spectral resolution).

Interpreting the results

V_LSR :		226.839 km/s
Velocity corrected wavelength :		157.860 microns
Plotted wavelength range :		157.058 - 158.663 microns
Interpolated values from data table:		
	Bandwidth =	0.802 microns
	MDLF =	2.085e-17 W/m^2
	MDCF =	0.570 Jy
Atmospheric Transmission :	0.775 (smoothed)	0.752 (unsmoothed)
Integration time (t_on):	18.862 (smoothed)	20.049 minutes (unsmoothed)

On-source total exposure time required is ~ 19 minutes

Considering the mapping strategy

Simple:

With a 3 x 3 mapping, step of 2.5 pixels (30''), we obtain a 2'x2' map which has:

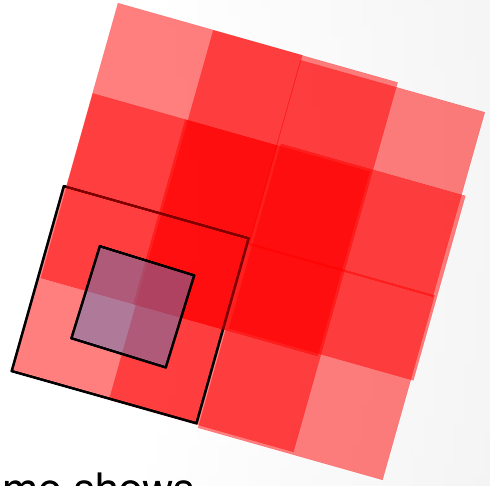
- Corners covered once
- Sides covered 2x
- Center covered 4x

Let's decide we want the sides to have at least 5σ sensitivity. Since we need 19 minutes for a 5σ observation, this means 19/2~8.5 min per position. Considering an exp. time per cycle of 30s, this means 17 cycles per position.

Let's assume that this coverage is enough for the parallel blue observation which will have a single coverage (since it has a FOV of 30''x30'').

Now we can enter these values into USPOT.

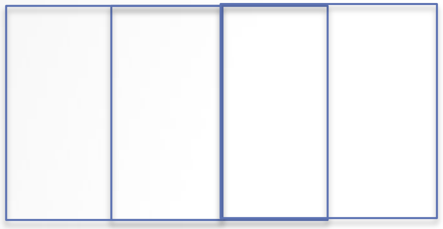
3x3 raster map



Frame shows single blue & red FOV

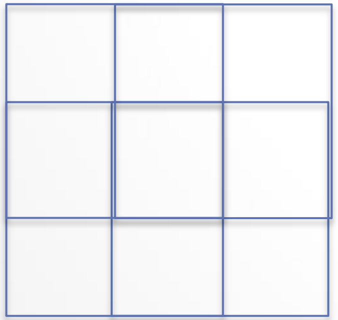
Considering the mapping strategy

Complex:

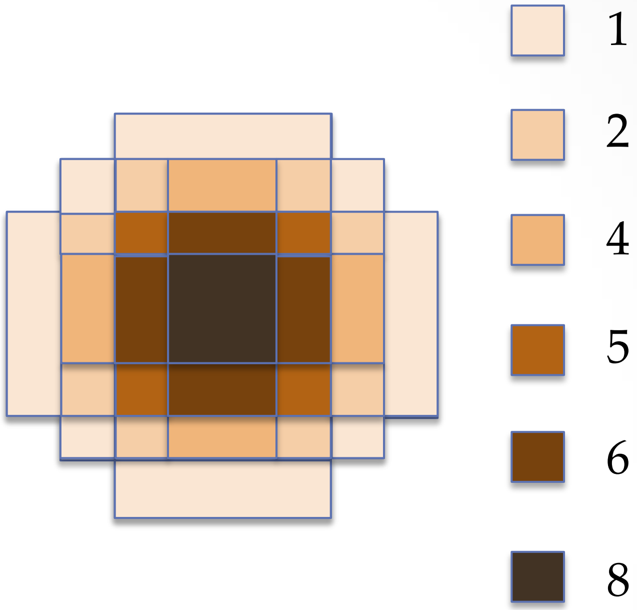


Horizontal scan through center (step 30")

Vertical scan through center (step 30")

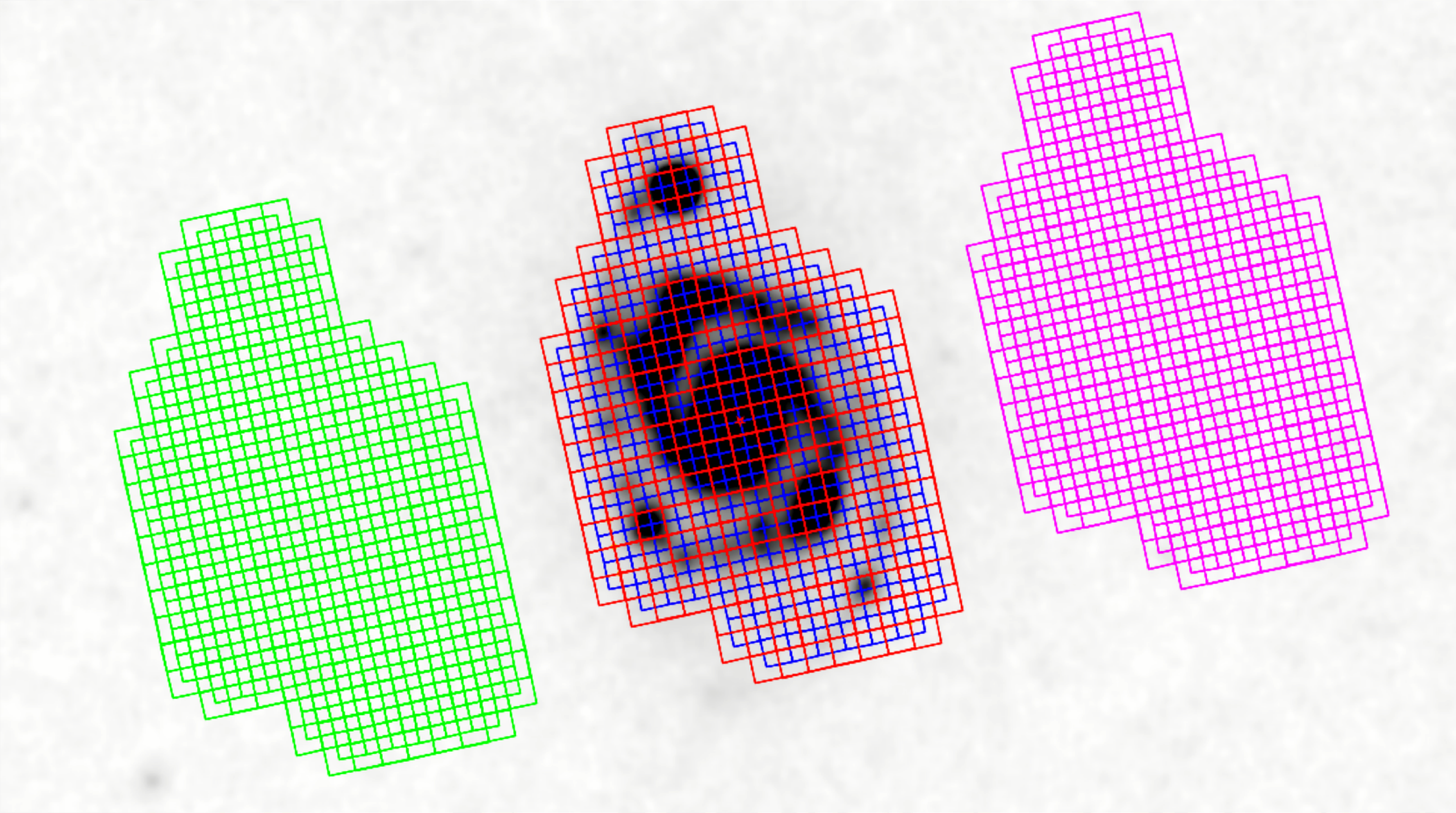


2x2 map with 30" steps



- Edges covered once
- Center covered 8x
- Other regions: 2-6x

A complicate map (M51)



15 h in several flights to cover the galaxy M 51 in C+ (240 fields, 90s on source, 10^{-17} W/m^2)

SOSPEX – display/analyze spectral cubes

To display FIFI-LS spectral cubes a new user-friendly Python GUI is available:

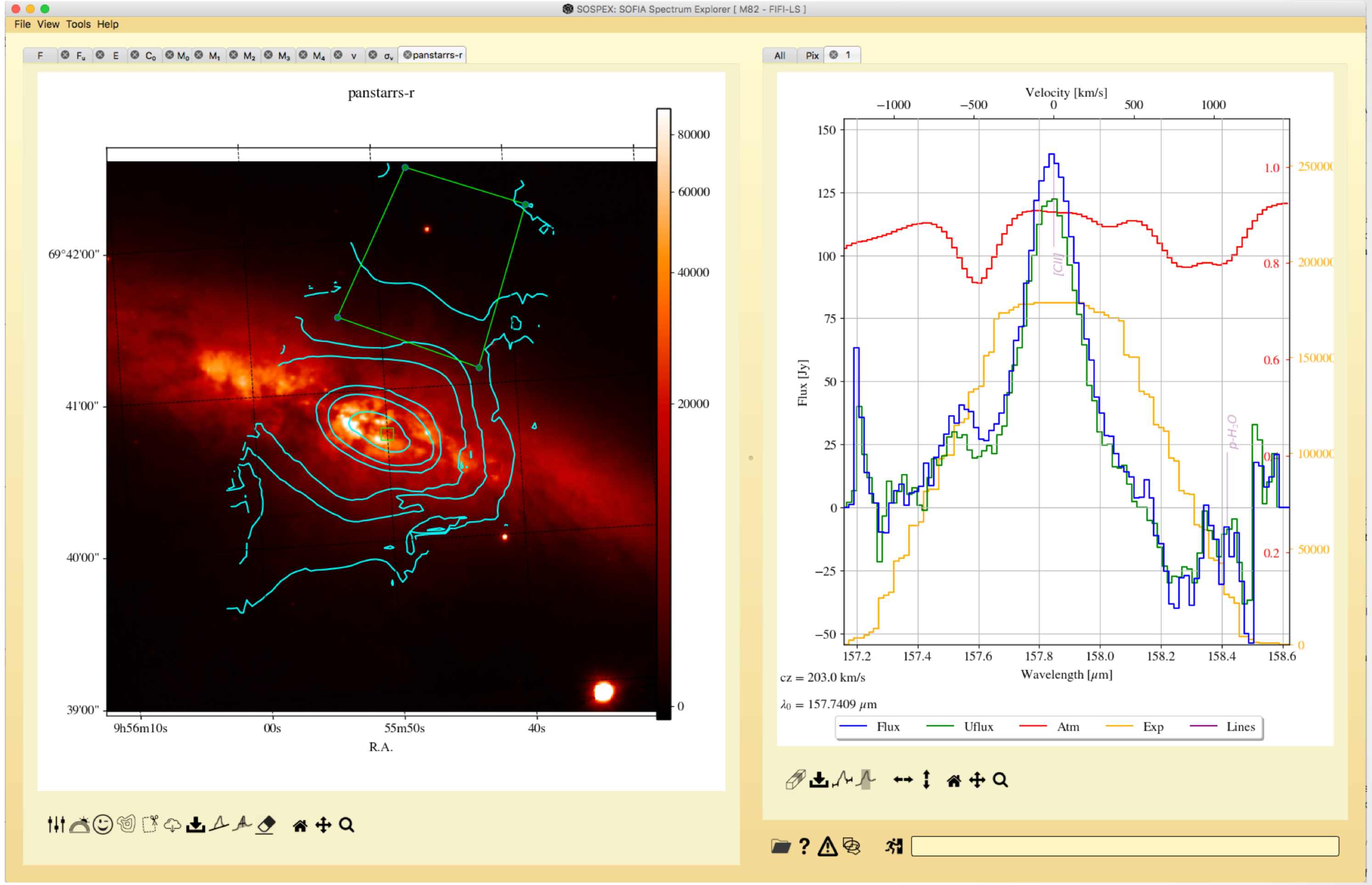
SOfia SPectral Explorer

The software can be installed via the anaconda installer:

conda install –c darioflute sospex

Capabilities:

- Read FIFI-LS, PACS, GREAT cubes
- Navigate cube planes and spectra through tabs
- Allow cube manipulations (cut/crop)
- Compute continuum and moments across cubes
- Extract flux in custom apertures
- Export/import defined apertures
- Download images from web archives
- Overlap contours on other images



M82 outflow observed with FIFI-LS overplotted on optical image

https://github.com/darioflute/sospex/blob/master/README.md

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Web links

- FIFI-LS Time estimator: https://atran.sofia.usra.edu/cgi-bin/fifi-ls/fifi.cgi

- FIFI-LS observer manual: https://www.sofia.usra.edu/science/proposing-and-observing/sofia-observers-handbook-cycle-6/3-fifi-ls

- FIFI-LS display/analysis GUI: https://github.com/darioflute/sospex/blob/master/README.md

- FIFI-LS workshop at the SOFIA Science Center: https://www.sofia.usra.edu/science/meetings-and-events/events/workshops/fifi-ls-workshop

- FIFI-LS first science results (SOFIA tele-talk): https://www.sofia.usra.edu/science/meetings-and-events/events/fifi-ls-science-observations

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