FIFI-LS: Basic Cube Analysis using SOSPEX

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1   INTRODUCTION

This data analysis recipe describes basic spectroscopic cube analysis using the SOFIA SPecturm Explorer (SOSPEX), a python tool written and maintained at the SOFIA Science Center by FIFI-LS pipeline scientist Dr. Dario Fadda. SOSPEX displays FIFI-LS and GREAT spectral cubes and allows the user to perform a number of basic analysis routines on them. In particular, the cube is shown as a 2D image (spatial image obtained as average along the wavelength dimension) and a spectrum (sum of spatial pixels of the original cube). The user can define apertures to compute the spectrum on the 2D image. It is possible also to crop the cube over the spatial image or cut it along the wavelength dimension. External images can be uploaded and overplotted on the spectral cube for comparison. A description of the FIFI-LS pipeline and data products can be found in the FIFI-LS GO Data Handbook which is available on the SOFIA Data Resources page.

2   INGREDIENTS

1. FIFI-LS GO Data Handbook for reference (latest version can be found on the SOFIA Data Resources page)

2. Download and install SOSPEX from github (https://github.com/darioflute/sospex/blob/master/README.md)

3. Download your *Level 4* (fully resampled, "WXY") data from the DCS archive; or follow along with the sample data identified below.
4. Look up spectral resolution for line(s) of interest from FIFI-LS Observers Handbook.

For this example, we will use the [CII] observations of M82 (red channel, ~158 μm, multi-flight Level 4 product). You can obtain this sample data from the DCS Archive:
- Navigate to https://dcs.arc.nasa.gov/ and sign in with your DCS credentials.
  - A DCS user account is required to download data from the archive. If you do not have an account, click "Register With DCS" under "User Support" and fill in the form there.
- After you have signed into the DCS, click on "Search Science Archive".
- On the Science Archive Search page, select/enter the following criteria and click "Submit":
  - Instrument: "FIFI-LS"
  - Processing State: "LEVEL_4"
  - Target: "M82"
- From the results page, select ObservationID = "P_2014-04-19_FI_F161R400537" and click "Get Selected Data in Current Page" and follow the download instructions. Be sure to save the file in a location that can be read by SOSPEX.

Once SOSPEX is started (see README with distribution), a two panel GUI should open with the following buttons in the lower right panel: **Load, Reload, Help, Report Issue, Choose aperture, exit, and status Bar.**

Tutorials are available by clicking on the **Tutorials** button (question mark icon below the right hand panel, on the left) or via **Help → Tutorials** on the menu system. You may want to step through some of the tutorials to familiarize yourself with the GUI.

3   INSPECTING THE CUBE

Load your cube using *File* → *Open Cube* (or the file open button – folder icon below the right hand panel, on the left):
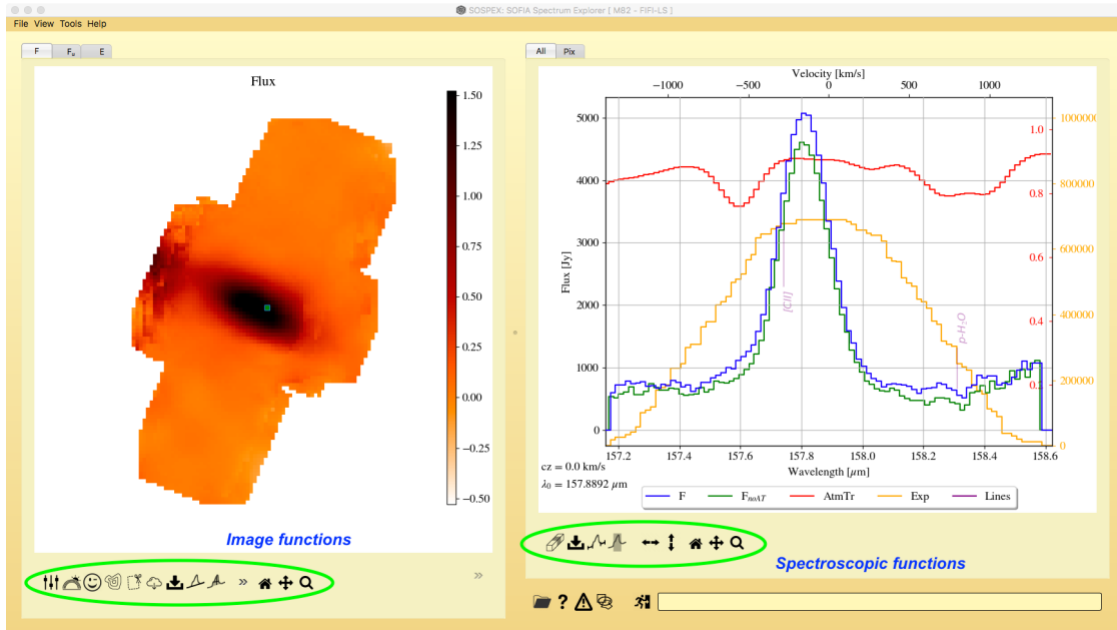
The left panel should have three tabs:
- *F*: median flux per spatial pixel over all spectral channels (Jy, with telluric correction)
- *F$_U$*: median flux per spatial pixel over all spectral channels (Jy, *without* telluric correction)
- *E*: exposure map in seconds per spatial pixel

A set of buttons should appear in the lower part of the left panel which provide quick access to functions available in the main menus at upper left:
- Adjust image levels
- Choose color map
- Blink between 2 images
- Contours
- Crop the cube
- Download image from cloud
- Save image
- Fit continuum
- Compute moments
- Erase a region (masking)
- Go back to original limits
- Pan figure

- Zoom in

In addition, the sky/pixel position and the flux are shown at the lower right for the current cursor location on the left panel.

Move the cursor around each of the images to get a feel for the total flux and exposure time per pixel, shown in lower right corner of the panel.

This is also a good time to change the image levels and color map if desired (buttons at lower left corner of panel). In this example, we have reversed the color map from the default.

The right panel shows the spectral dimension and should have 2 tabs:
- *All*: Total flux as a function of wavelength summed over all spatial pixels.
- *Pix*: Spectrum of the *selected* pixel in the image panel.

There should be a set of buttons at the bottom of the right panel as well that provide quick access to common spectroscopic tasks available in the main menu items at the upper left:
- Trim the cube (in wavelength space)
- Save current spectrum
- Draw continuum segments
- Define a wavelength slice (for moment calculation or display)
- Resize figure horizontally/vertically
- Go back to original display
- Pan figure
- Zoom in

The spectra include the corrected (blue) and uncorrected (green) flux (F, F_U) as well as the exposure spectrum (yellow; seconds per wavelength bin), and the atmospheric transmission spectrum (red) – smoothed to the FIFI-LS resolution. Also shown are the locations of prominent astrophysical lines (purple). One can add and remove the different curves from the figure by clicking on the labels below the figure panel.

In regions of broad and/or relatively weak telluric absorption features, the corrected flux spectrum is expected to be accurate based on experience with both FIFI-LS and FORCAST. Some spectral regions (particularly at 63 μm) contain telluric features that cannot be corrected very well because they are either very sensitive to atmospheric conditions (and hence cannot be accurately modeled by ATRAN post-facto) or very deep and narrow (or both). (See the FIFI-LS data handbook for further discussion.) Hence, the uncorrected spectrum is also shown so that the user can assess the telluric correction.

Switching to the "Pix" tab allows the user to inspect the spectrum at each pixel by moving (click and drag) the highlighted pixel in the left panel:
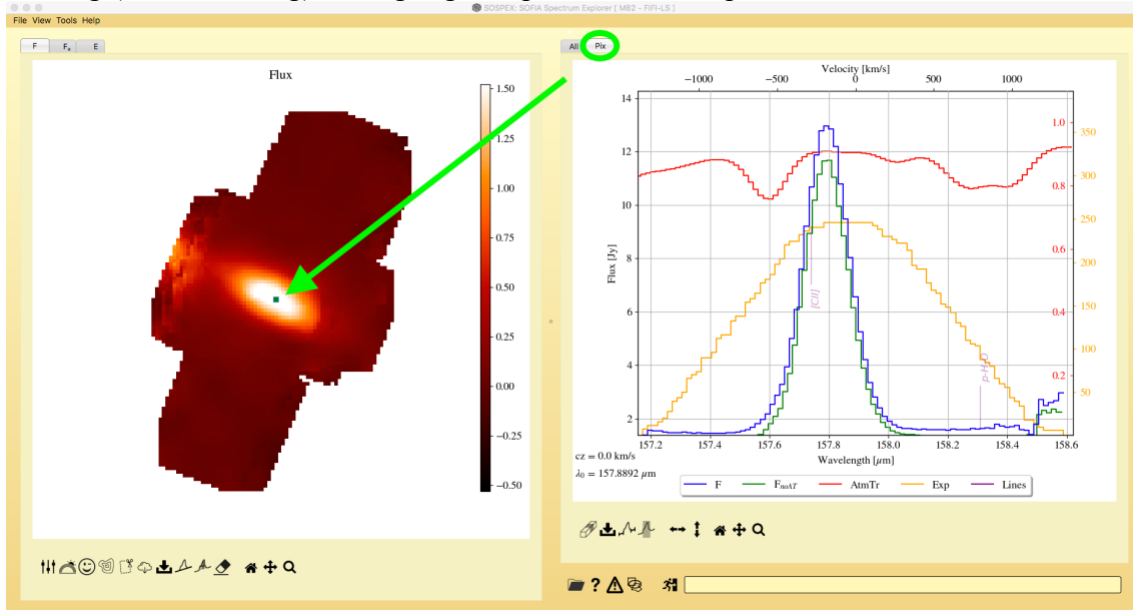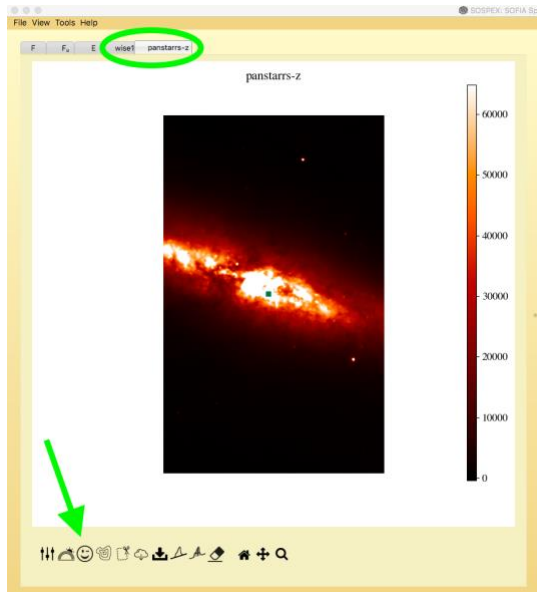

Again, drag the highlighted pixel around the image in order to get a sense of the overall line strength and shape as a function of position across the cube, and especially in regions of interest.

4   COMPARING TO A REFERENCE IMAGE

It is often very instructive to compare images in the IR with those at other wavelengths. SOSPEX provides access to some online surveys which can be very useful in understanding the data at longer wavelengths. Use the *File → Import Image* function to load a survey image from the list, or one of your own from disk ('local' at the top of the Selection window).

For M82 we have loaded both the WISE Band 1 (3.4 μm) and Pan-STARRS *z*-band images for comparison. The images are automatically registered with the FIFI-LS cube and displayed in separate tabs in the left panel. You will need to select the tab to view the image:


You can then "blink" between any two tabs to better compare the survey image with the FIFI-LS data.

In the case of M82, the strongest [CII] emission comes from the central part of the galaxy, but by moving the highlighted pixel around (click and drag) you can see that there is significant emission (from the outflow) coming from above and below the plane as well:
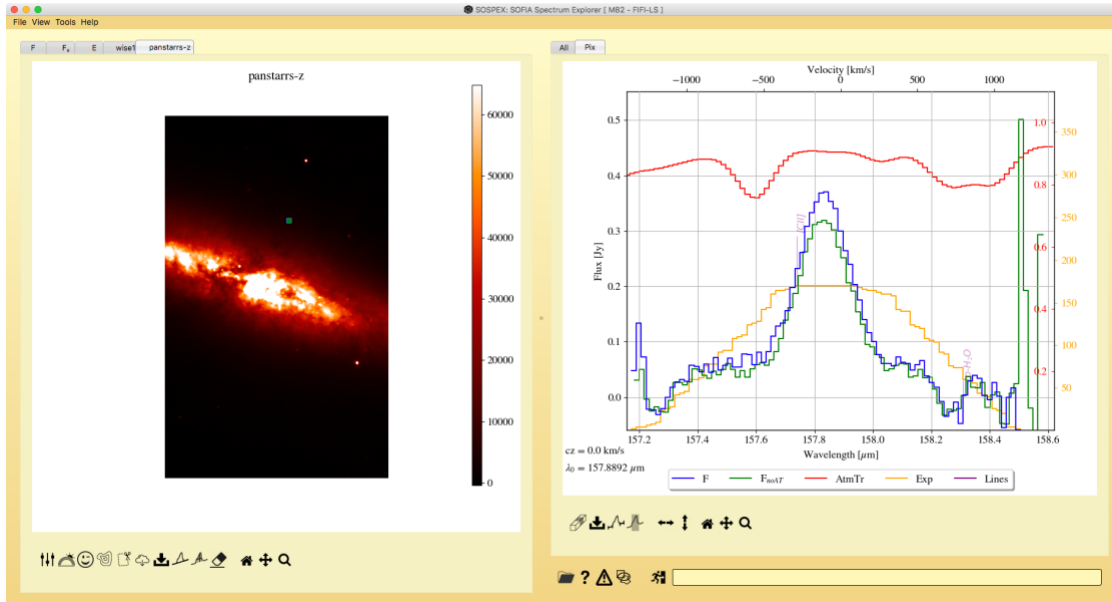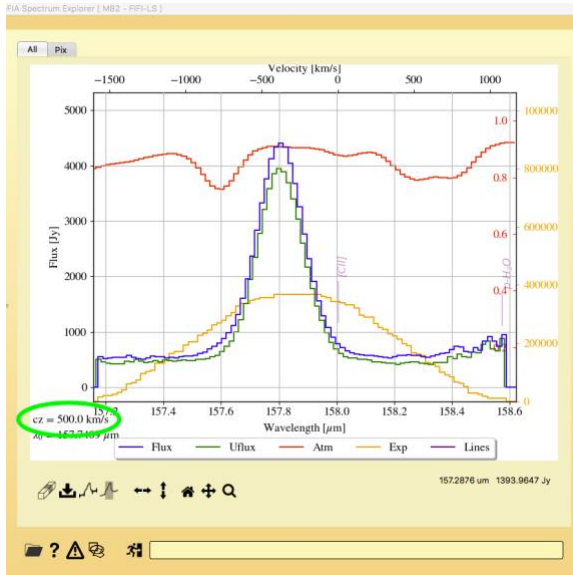
5   REFERENCE VELOCITY AND REDSHIFT

The reference velocity shown at the top of the spectrum panel is initially set to the central wavelength pixel. To reset the reference wavelength to that of a line of interest, simply click on the line identification (in purple) and select 'yes' when asked if you want to update the reference wavelength:
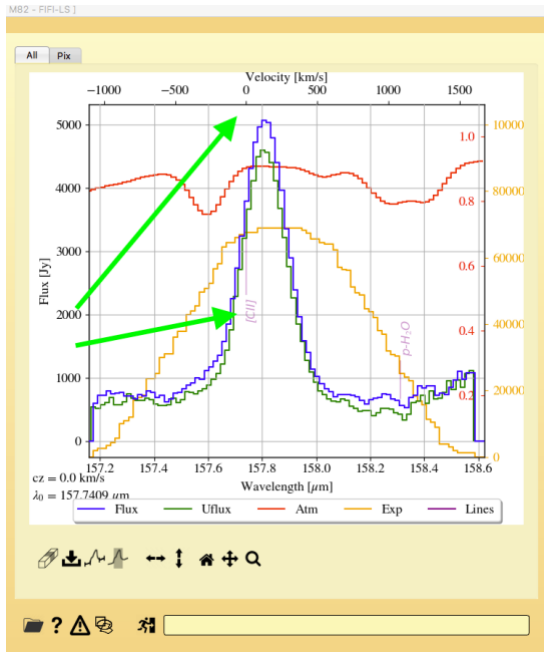
Alternatively, click on the bottom left of the plot over the λ_0 label to insert a reference wavelength of your choice.

The cz value is shown at the bottom of the plot. If the FITS header contains the velocity information from USPOT (data taken since ~2017) then this will be entered here automatically. Otherwise it will default to zero. A redshift can be applied to the scale by clicking on the cz value; this shifts the velocity scale and the line identification:


It's also possible to move the reference line and determine the resulting redshift by clicking the line identifier (in purple) and dragging to the new position in velocity.

6   TRIMMING, CROPPING, AND MASKING

It is often advantageous to remove parts of the cube which are either not of interest, or that suffer from observation/data reduction artefacts. (We do not recommend, however, removing regions simply because they have low S/N.) For example: in the case of M82, the east (left) side of the cube suffers from artefacts, which can be seen in the total flux and also in the spectra of individual pixels:
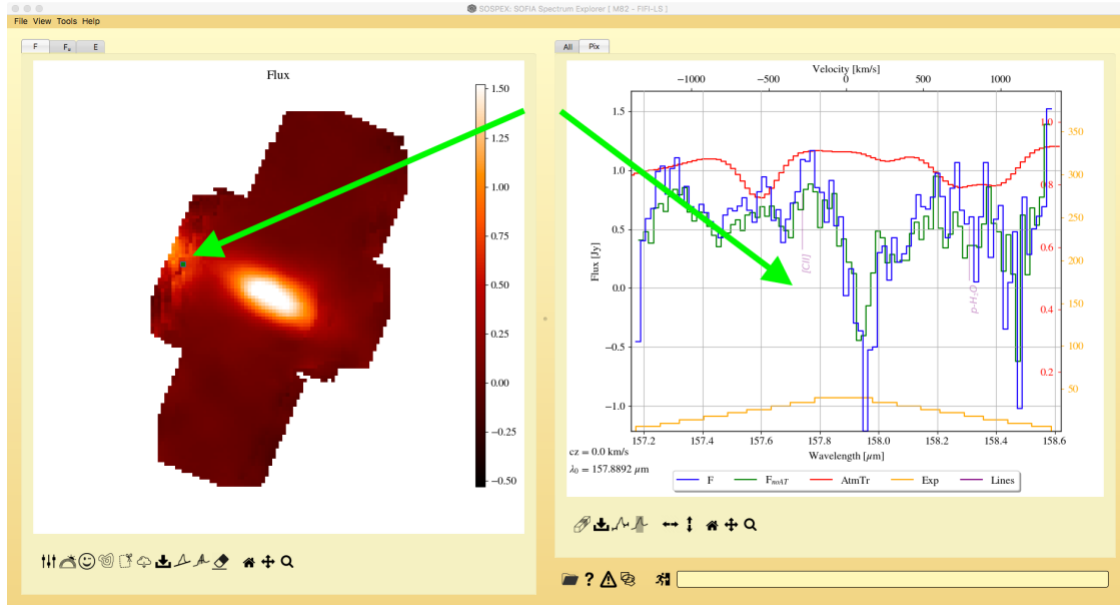

This corresponds to a region of low exposure as seen in the coverage map:
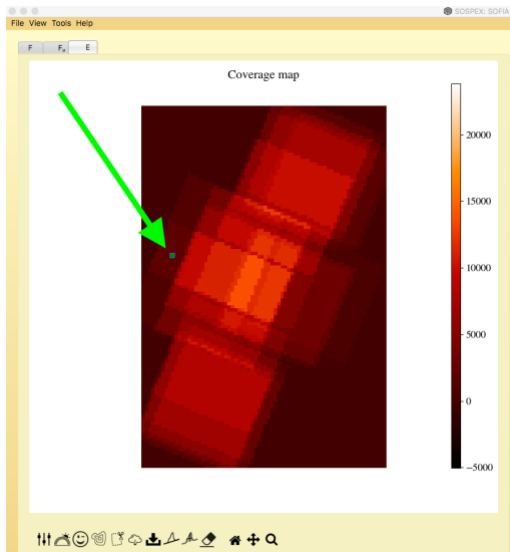
In order to prevent this region from skewing later calculations, we can mask it using the *Erase* tool. In this case we will mask only the region with low exposure coverage.

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Select **Tools → Mask part of cube → …*inside a polygon*** (or click the eraser tool at the bottom of the left panel) and then use the cursor to identify the corners of the region:
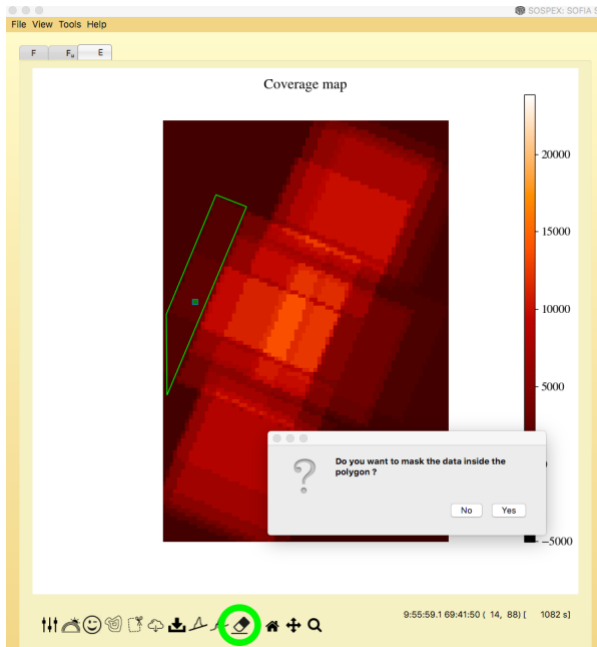

After confirming the region, switch back to the Flux tab to see the results:
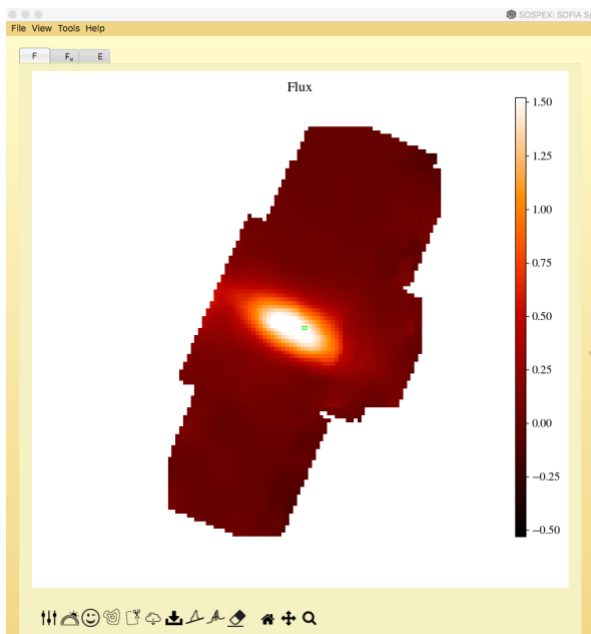
(One can also simply crop the cube, see the Tutorials for instructions.)
The spectral dimension of the cube sometimes suffers from edge effects due to the observation and/or poor telluric correction. The spectral edges of the cube can be

trimmed using the **Trim** tool. In the M82 case, we will trim the long wavelength edge at about 158.4 µm. Select **File ➔ Save cube ➔ Trimmed**, and identify the spectral region to *keep* by clicking and dragging over a region in wavelength space:
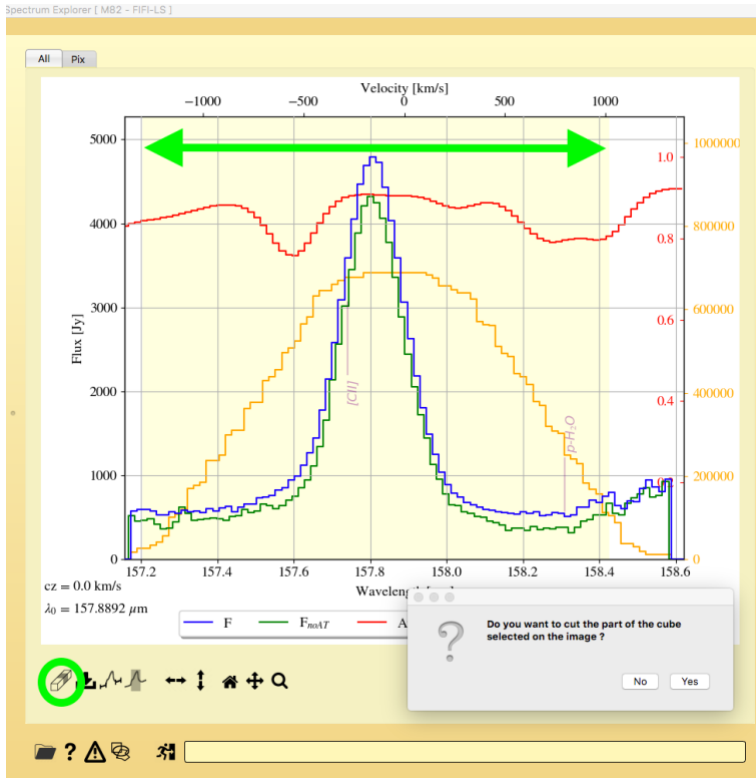
After confirming the region, the cut region will be saved to a separate file. Now use **File ➔ Open Cube** to load the newly created cut and masked cube.

7 WORKING WITH APERTURES

It is sometimes desirable to sum over a sub-region or fixed aperture in order to compare with other datasets. In the case of M82 we might want to sum over only the central part of the galaxy, rather than the whole image. Use the *Aperture* tool (button below the right panel or in *Tools* ➔ *Select aperture* ➔ *Ellipse*) to define an elliptical aperture and place it over the central part of the galaxy (note that the initial definition only draws an ellipse with axes in x in y; once the ellipse is placed it can be tilted, moved and re-sized as required):
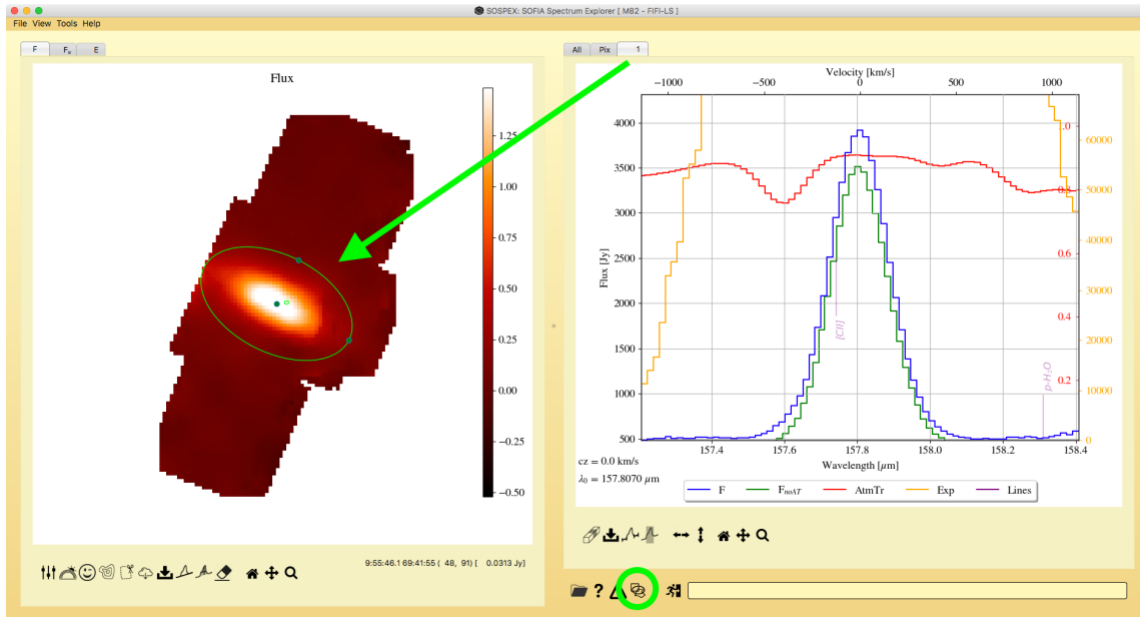

The spectrum summed over all pixels in the aperture is now shown in tab "1" in the right panel. The aperture spectrum as well as the aperture can both be exported for comparison to other datasets using the *Save Spectrum* (*File* ➔ *Save spectrum* or button at the bottom left of the right panel) and *File* ➔ *Aperture I/O* ➔ *Export* functions (see the Tutorials for additional details). Once finished with the aperture, you can remove it by selecting the aperture and then hitting "d".

8 FITTING THE CONTINUUM

Determining the properties of the emission line throughout the cube is done by calculating velocity moments. But before that can be done, the continuum must be fit. Select *Tools* ➔ *Fit Continuum* ➔ *Define Guess* (or use the *Fit Continuum* button at the bottom left of the right panel) to identify the 2 wavelength regions to use across the cube for continuum fitting. A dialog will pop-up for the continuum parameters:

- **Function**: Can be either a "Constant" offset or a linear "Slope", as appropriate for the data.
- **Boundary**: Set to "Positive" to prevent a constant offset from being below zero, if you know this would be unphysical.
- **Kernel**: This is the unweighted spatial kernel (single pixel, 5 pixels in a + shape, 9 pixels in a box) used to determine the flux at each wavelength. Larger kernels provide better S/N for the continuum fit and are usually the best option.

After selecting your parameters (in this example we use Function = "Slope", Boundary = "None", and a 9-pixel kernel), click and drag the mouse to identify two regions on the spectrum panel for continuum fitting throughout the cube. *This must be done on the "Pix" tab, but the spectral selection will automatically extend to all pixels.* Use the "All" tab to identify the approximate regions, and then switch to the "Pix" tab to actually select the regions:
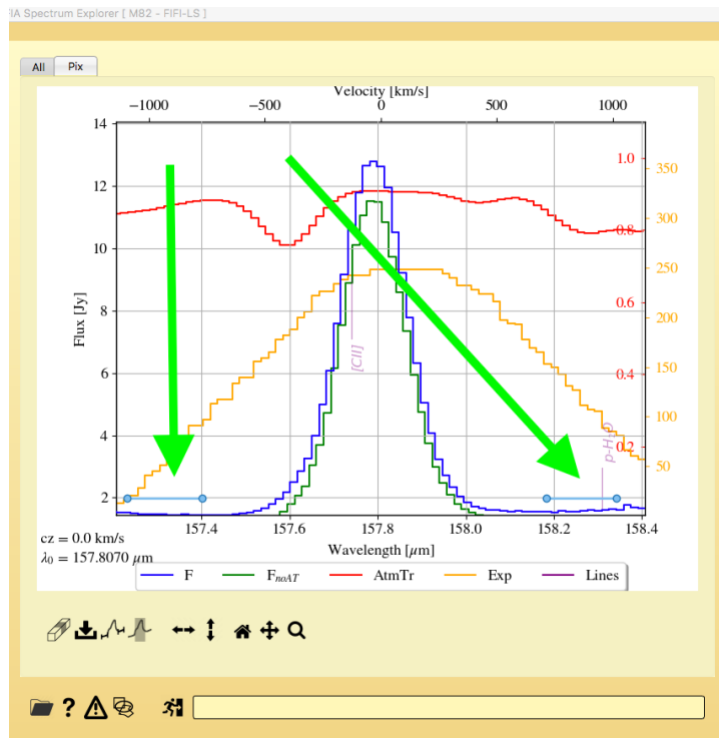
Then select **Tools → Fit Continuum → Fit All Cube**. When the fitting is complete, a new tab will appear in the left panel called C_0 which shows the continuum flux at the reference wavelength, and a light blue line is shown in the right hand spectrum panel showing the fitted continuum:
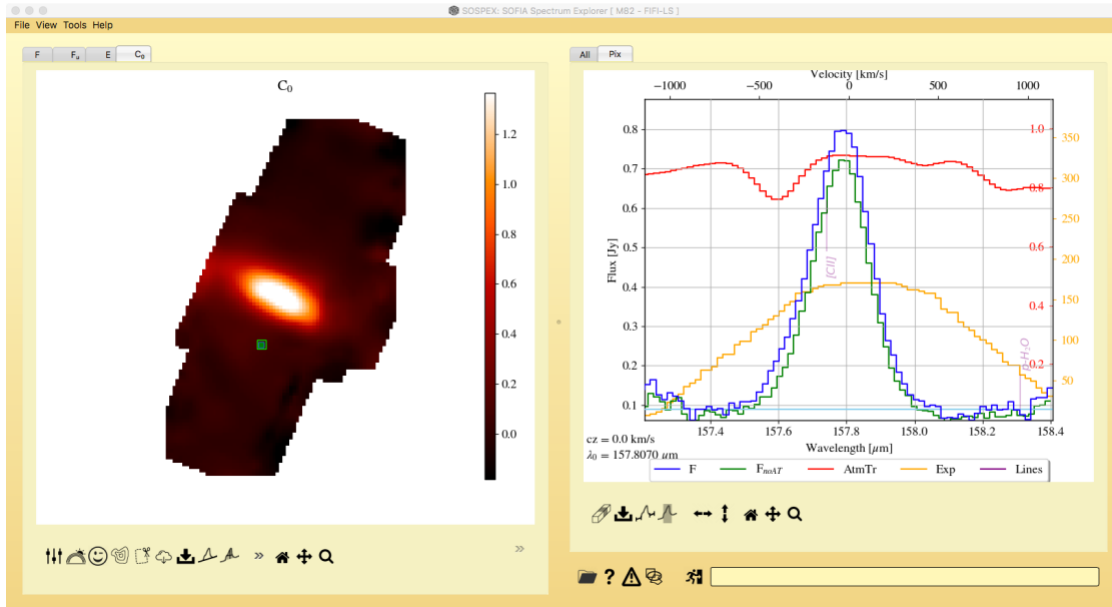

If desired, the user can then subtract off the continuum and save the results using **File → Save cube → Continuum subtracted**, and then open the continuum subtracted cube.

9   CALCULATING LINE INTENSITY AND VELOCITY MOMENTS

Once the continuum is fit, the line intensity and velocity moments can be calculated (see the tutorial for a definitions of the various moments). To select the wavelength region over which to calculate the moments, select **Tools → Compute moments → Define slice**. Again, this must be done on the "Pix" tab, but it is helpful to use the "All" tab to identify the wavelength region desired:
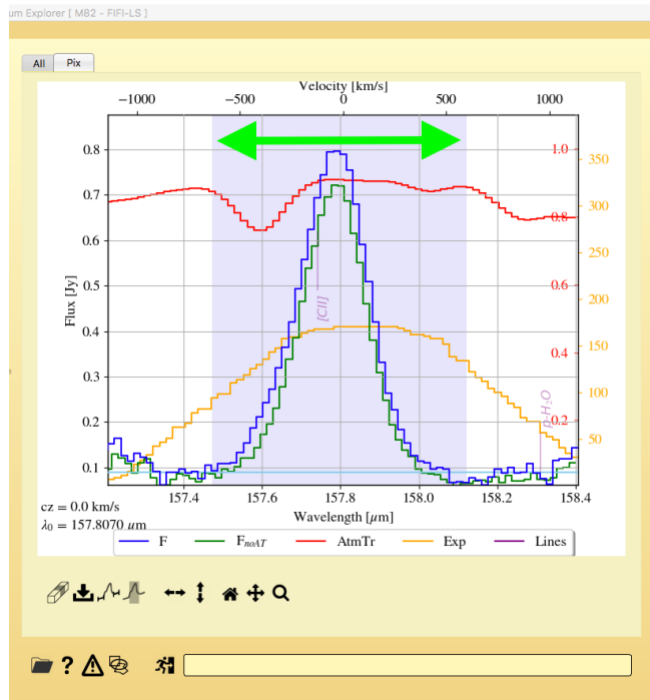
Once the wavelength region has been defined, simple select **Tools → Compute Moments → Compute all cube** (note that for larger cubes it may take a minute or so to complete the calculations). When done, a number of new tabs will appear in the left panel: one for each moment, along with velocity and dispersion (which are derived from the M1 and M2 moments respectively):
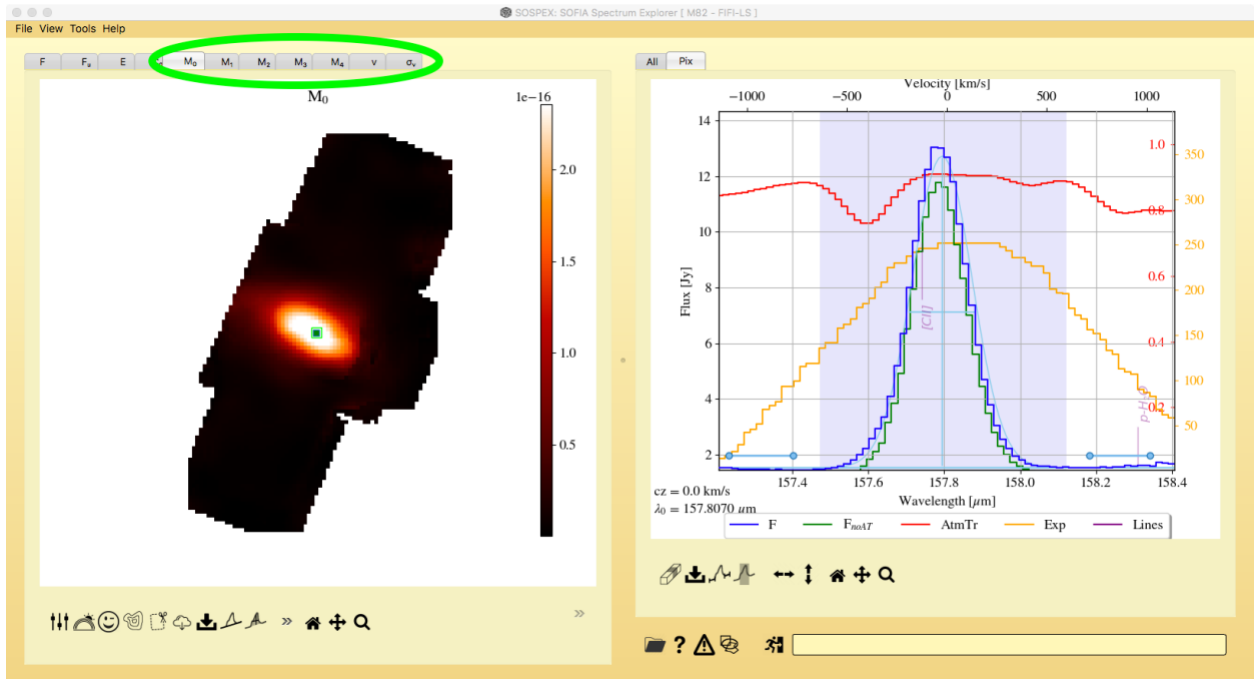

The right hand panel now also shows a model Gaussian using the calculated moments overplotted in light blue for each pixel. Note that this is *not a fit*, but a model line for comparison. For high S/N lines, the profile should match the model Gaussian fairly closely. However, for weaker lines, the actual profile may be much narrower.

The M_0 moment corresponds to the line intensity. The total intensity at each pixel is given in W/m^2. It is usually desirable to compare the total intensity with the velocity and dispersion maps. The easiest way to do this is to make a contour plot of the intensity, which will then be displayed on all other tabs. With the M_0 map selected, press the *Contour* button at the bottom to generate the default set of contours for the image:
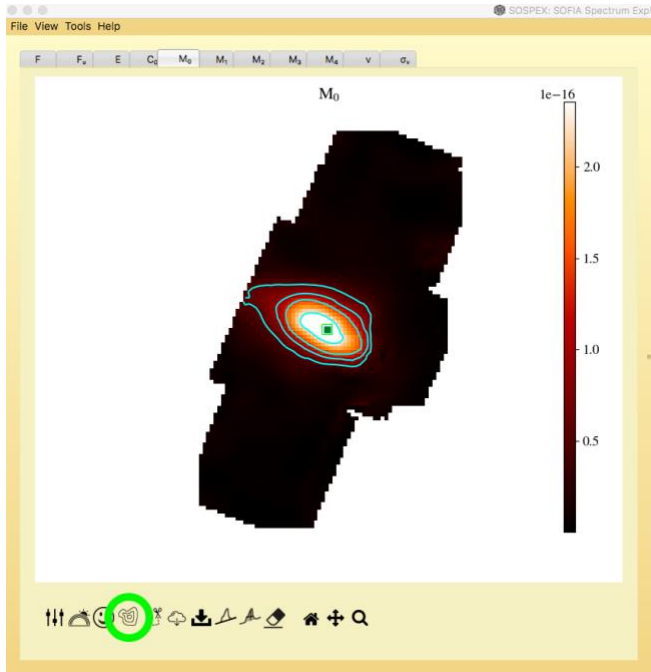

Use the contour tutorial for instructions on how to modify the contour plot. In some cases, it is useful to add a few more contour lines to better illustrate any gradients.

Now switch to the velocity map (v tab) to compare the velocity field to the line intensity; you will probably want to switch back to linear scaling and perhaps change the color map for the velocity display (both done using the buttons below the left panel). If you click the **_Adjust Image Levels_** button at the bottom, you can restrict the display to the velocity regions of interest. In the case of M82 we would like to restrict the display to levels around the average velocity:
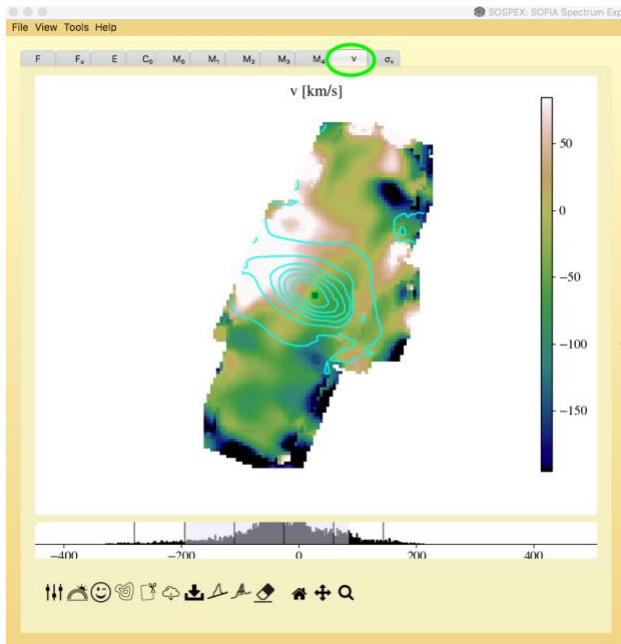
There appears to be a strong gradient in the velocity that bisects the long axis of the line emission: which is what we would expect for an edge-on rotating galaxy. The gradient can also be seen in the spectra at each pixel by dragging the pixel in the left-hand panel along the long axis of the intensity contours:
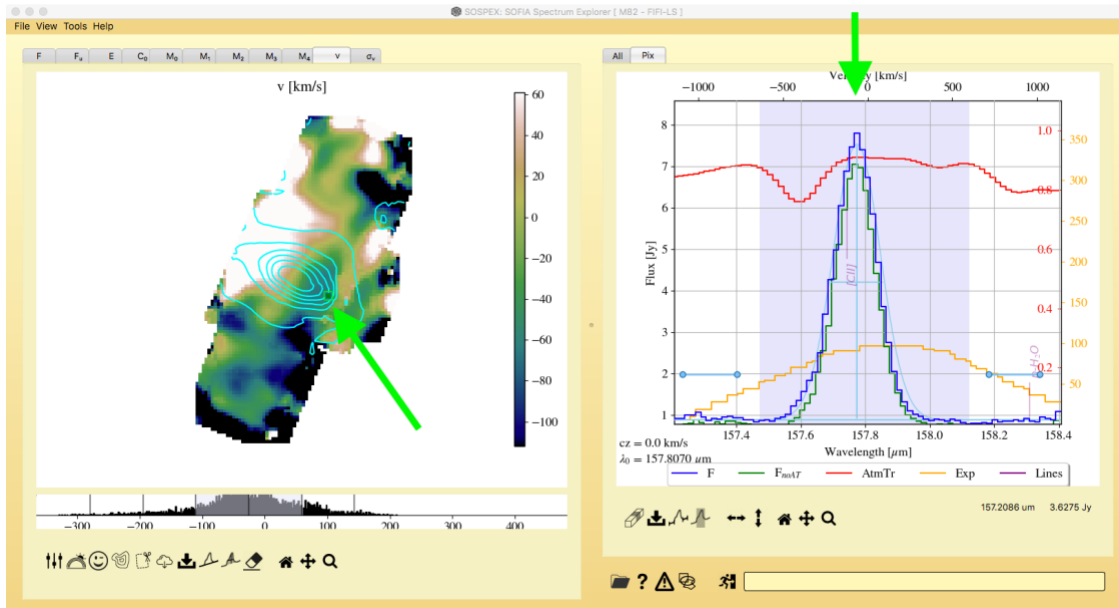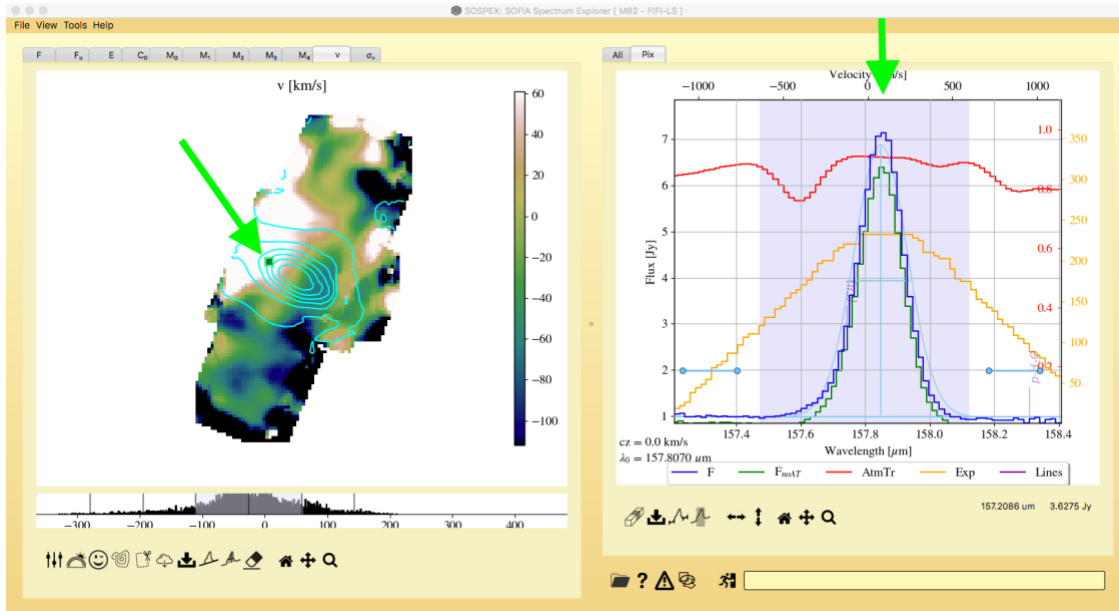
Switching to the dispersion map (σ_V tab), we can evaluate the width of the line as a function of position across the map:
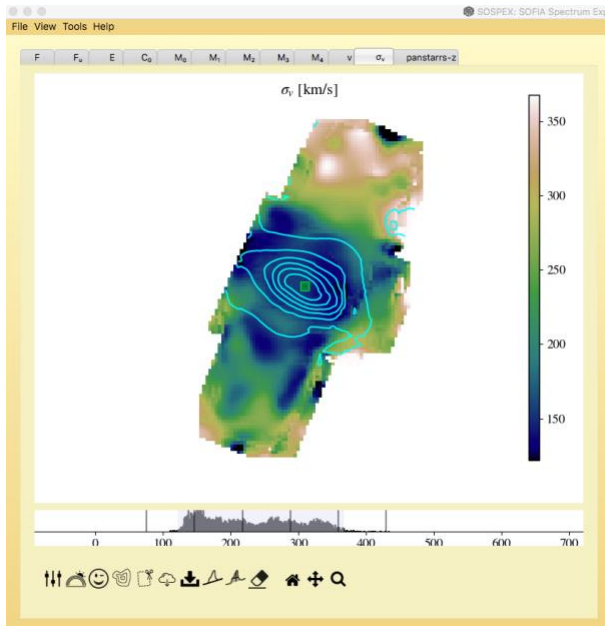
It is important to look up the resolution of the instrument (see the FIFI-LS section of the Observers Handbook) in order to evaluate the dispersion map. In this case, the resolution of FIFI-LS is approximately R = 1250 at 157.8 μm. So, an unresolved line will have a FWHM of 240 km/s which corresponds to a instrumental dispersion of σv = 102 km/s. To obtain the real dispersion one should deconvolve the measured line width from the instrumental width.

As can be seen from the levels, the line widths across the cube are slightly higher than the resolution and hence the line is marginally resolved. (Note that the high values in the northern and southern edges of the cube coincide with regions of low S/N and are suspect.)