



# NHSC/PACS Web Tutorials

## Running PACS spectrometer pipelines

### PACS-302

*Level 1 to Level 2 and beyond:  
From Sliced Cubes to Rebinned and  
Projected Spectral Line Cubes, and 1-D Spectra*

Original Tutorial by Philip Appleton

Updated Sept 2012 by Steve Lord

Updated Feb 2013 by Steve Lord

Updated Oct 2013 by Steve Lord

Updated May 2014 for HIPE 12.0.0 by David Shupe

Updated June 2015 for HIPE 13.0.0 by Roberta Paladini

# Introduction

This tutorial presents the main steps of the standard pipeline starting from the calibrated Frames (Level 1) and pacsCube (also Level 1).

It describes the processing steps needed to create a set of Pacs “Rebinned Cubes “ and (especially if the observation is a raster) a Projected, Drizzled or specInterpolated Cube.

Numerous break points are shown, where one can interactively examine the intermediate results of the pipeline.

**The PACS Spectroscopy pipelines are documented here:**  
*PACS Data Reduction Guide: Spectroscopy*, e.g., Chapter 3  
These documents can be accessed through the HIPE help pages.

## Welcome to the Herschel Interactive Processing Environment Help System



The screenshot shows a grid of nine help topics. A callout bubble points to the 'Learn about PACS data' box. The callout bubble contains the text: 'Learn about PACS data', 'Data reduction guide for photometry and spectroscopy', and 'Data known issues'.

 <p>New to HIPE? Click here for a <a href="#">quick introduction</a></p>	 <p>Learn about the Help System: <a href="#">Help on Help</a></p>	 <p>Learn how to get data from the <a href="#">Herschel Archive</a></p>
 <p>Learn about HIFI data • <a href="#">Data reduction guide</a> • <a href="#">Pipeline specification</a> • <a href="#">Data known issues</a></p>	 <p>Learn about PACS data • Data reduction guide for <a href="#">photometry</a> and <a href="#">spectroscopy</a> • <a href="#">Data known issues</a></p>	 <p>Learn about SPIRE data • <a href="#">Data reduction guide</a> • <a href="#">Pipeline specification</a> • <a href="#">Data known issues</a></p>
 <p><a href="#">HIPE known issues</a></p>	 <p>Find out <a href="#">what's new</a></p>	 <p>See a list of all the <a href="#">available manuals</a></p>



Important additional material for each release is found online  
at the PACS public Twiki:

<http://herschel.esac.esa.int/twiki/bin/view/Public/PacsCalibrationWeb>

Also, find out what is new for pipeline 13 here:

<http://herschel.esac.esa.int/twiki/bin/view/Public/HipeWhatsNew13x#Pipeline>



## Tutorial Pre-requisites:

1. HIPE is running version 13.0.0 (or user build 13.0.5130) or later
2. You have completed the following tutorial:
  - ***PACS-301 PACS Spectroscopy Level 0 to 1 Processing***

At this point in the processing we had just completed the last step of tutorial PACS 301. We last performed the flat field step after having created a set of sliced Cubes (step 3 below). We also did some cleanup (steps 4 & 5 below)

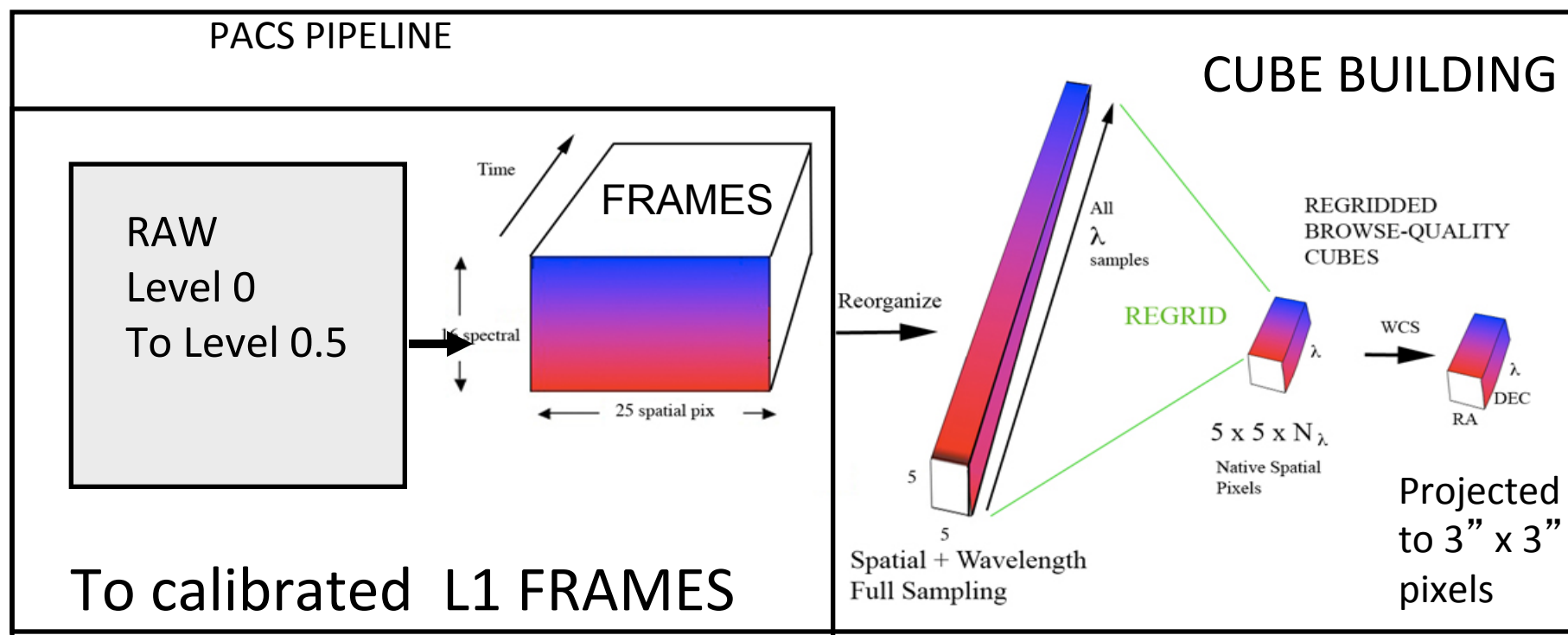
In this tutorial we continue working with obsId = 1342250905  
camera = blue

Our last steps which brought us to Level 1:

```
341 # 3. Actual spectral flatfielding
342 # slopeInContinuum is a boolean. Set it to true for lines existing on a continuum with a significant
343 slopeInContinuum = 1
344 slicedCubes = specFlatFieldLine(slicedCubesMask, scaling=1, copy=1, maxrange=[50.,230.], slopeInConti
345
346 # 4. Rename mask OUTLIERS to OUTLIERS_B4FF (specFlagOutliers would refuse to overwrite OUTLIERS) & de
347 slicedCubes.renameMask("OUTLIERS", "OUTLIERS_B4FF")
348 slicedCubes = deactivateMasks(slicedCubes, String1d(["INLINE", "OUTLIERS_B4FF"]))
349
350 # 5. Remove intermediate results
351 del waveGrid, slicedRebinnedCubes, slicedCubesMask
352
353 # --- End of Spectral Flat Fielding
354
355 # -----
356 #           Processing           Level 1 -> Level 2
357 # -----
```

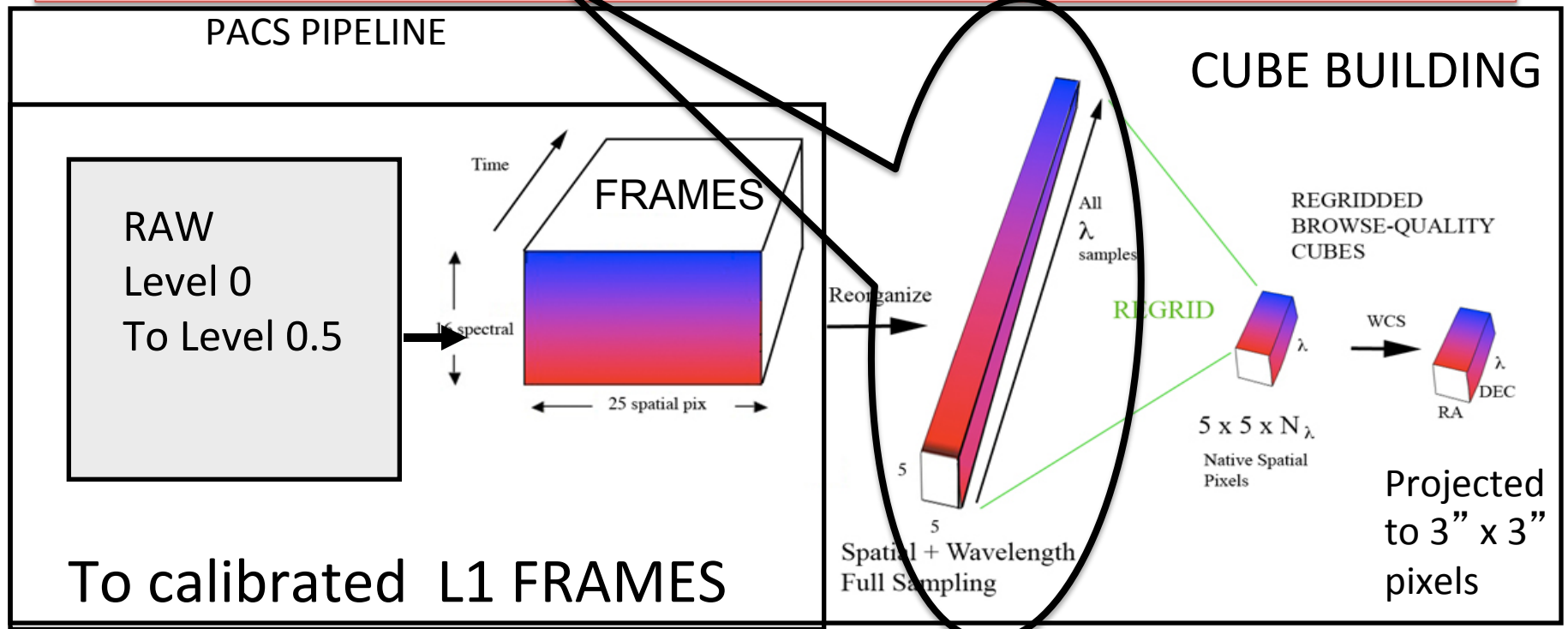
Let's recap the structure of the data products so far, and see where we are going:

## Level 0 -1, and Level 2 Products



Let's recap the structure of the data products so far, and see where we are going:

Near the end of the Level 1 pipeline, we created a set of pacsCubes. There are 6 pacsCubes in our example, because this blue AOR contains 6 slices (Nod A and Nod B for each cycle position of the only observed line)





# Level 1 to 2 overview:



Step 1

Check number of Frame and Cube Slices from level 1

Step 2

Create a wavelength grid for binning

Step 3

Flag data with user-controlled sigma-clipping

Step 4

Create the rebinned cube and average the NODS

Step 5

Inspect the Rebinned Cube Spaxel-by-Spaxel

Step 6 (*for Raster or dither pattern mapping of extended sources*)

Project Rebinned Cubes (via specProject , Drizzling or specInterpolate) onto a WCS

Step 6 (*for point sources and single pointings*)

Extract spectra from the central pixel

Step 7

Explore Rebinned and Projected cubes in Spectrum Explorer





# Step 1

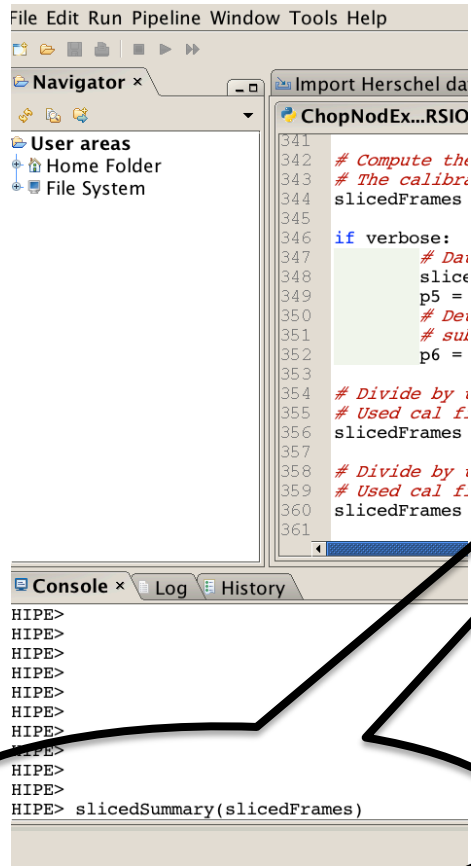
Check that you have converted your frames to pacsCubes (5 x 5 x N) product, and that you have the correct number of both



A pacsCube is simply a reorganized Frame with dimensions which are  $5 \times 5 \times N$  where the  $5 \times 5$  refers to the IFU spaxels of PACS, and  $N$  is the number of time samples which translate into grating position and wavelength. In a sense you can think of the pacsCube as a spatial representation of sky ( $5 \times 5$ ) and the third dimension can be translated into wavelength—forming the basic dataset or “cloud of wavelength samples” as a function of position.

In our example we had 6 slices of Frames. Now, having executed the last step, we have 6 slices of Cubes. These slicedCube and slicedFrame entities (objects) are simply collections of Frames and Cubes sliced by raster position (if relevant), Nod position (Nod A and B) and Line ID. In this case we have one line observed with two Nod observations and three Nod cycles.

# Check One—Let's check that we have the correct number of level1 Frames and pacsCubes



Type into the Console window the following

```
slicedSummary(slicedFrames)
slicedSummary(slicedCubes)
```



## Summary of Level 1 Products



HIPE> slicedSummary(slicedFrames)

noSlices: 6

noCalSlices: 0

noScienceSlices: 6

slice#	isScience	nodPosition	nodCycle	rasterId	lineId	band	dimensions	wavelengths
0	true	["B"]	1	0 0	[2]	["B3A"]	[18,25,1536]	62.936 – 63.441
1	true	["A"]	1	0 0	[2]	["B3A"]	[18,25,1536]	62.936 – 63.441
2	true	["A"]	2	0 0	[2]	["B3A"]	[18,25,1536]	62.936 – 63.441
3	true	["B"]	2	0 0	[2]	["B3A"]	[18,25,1536]	62.936 – 63.441
4	true	["A"]	3	0 0	[2]	["B3A"]	[18,25,1536]	62.936 – 63.441
5	true	["B"]	3	0 0	[2]	["B3A"]	[18,25,1536]	62.936 – 63.441

Above are 6 Frames (18x25x1536) representing 1+16+1 (=18) spectral pixels, 25 spatial pixels (the 5 x 5 array) and 1536 time samples. Note the 16 spectral pix plus 2 extra (a "open" channel and an "overscan") making 18 spectral pixels total

HIPE> slicedSummary(slicedCubes)

noSlices: 6

noCalSlices: 0

noScienceSlices: 6

slice#	isScience	nodPosition	nodCycle	rasterId	lineId	band	dimensions	wavelengths
0	true	["B"]	1	0 0	[2]	["B3A"]	[24576,5,5]	62.936 – 63.441
1	true	["A"]	1	0 0	[2]	["B3A"]	[24576,5,5]	62.936 – 63.441
2	true	["A"]	2	0 0	[2]	["B3A"]	[24576,5,5]	62.936 – 63.441
3	true	["B"]	2	0 0	[2]	["B3A"]	[24576,5,5]	62.936 – 63.441
4	true	["A"]	3	0 0	[2]	["B3A"]	[24576,5,5]	62.936 – 63.441
5	true	["B"]	3	0 0	[2]	["B3A"]	[24576,5,5]	62.936 – 63.441

After conversion to slicedCube we now have 6 pacsCubes, organized as time sample\*16 (=24576), 5 x 5 in this case. Note that the open and overscan spectral pixels have been stripped off in the pacsCube format.



## Step 2

Create a wavelength grid. This will be used to grid the spectrum in “wavelength-space” and is the first step in constructing a re-binned cube. In the default case the grid is Nyquist-sampled. However, the user can select a finer grid or, alternatively, a courser grid to effectively provide additional smoothing.



Creating a wavegrid: the grid resolution and number of phased samplings are governed by the parameters “oversample” and “upsample”, respectively. The default values of these are oversample = 2, upsample = 4. The default values provide a grid which oversamples the intrinsic spectral resolution element by a factor of 2 (i.e., Nyquist sampling). An upsample value of 4 means that four contiguous sets of wavelength bins are laid-out. When oversample is “m”, the binwidth used is the intrinsic resolution element/m. When upsample is “n”, n sets of wavelength bins are laid-out, each phased by the binwidth/n.

```
waveGrid=wavelengthGrid(slicedCubes.refs[0].product, oversample=2, upsample=4,  
                        calTree = calTree)
```

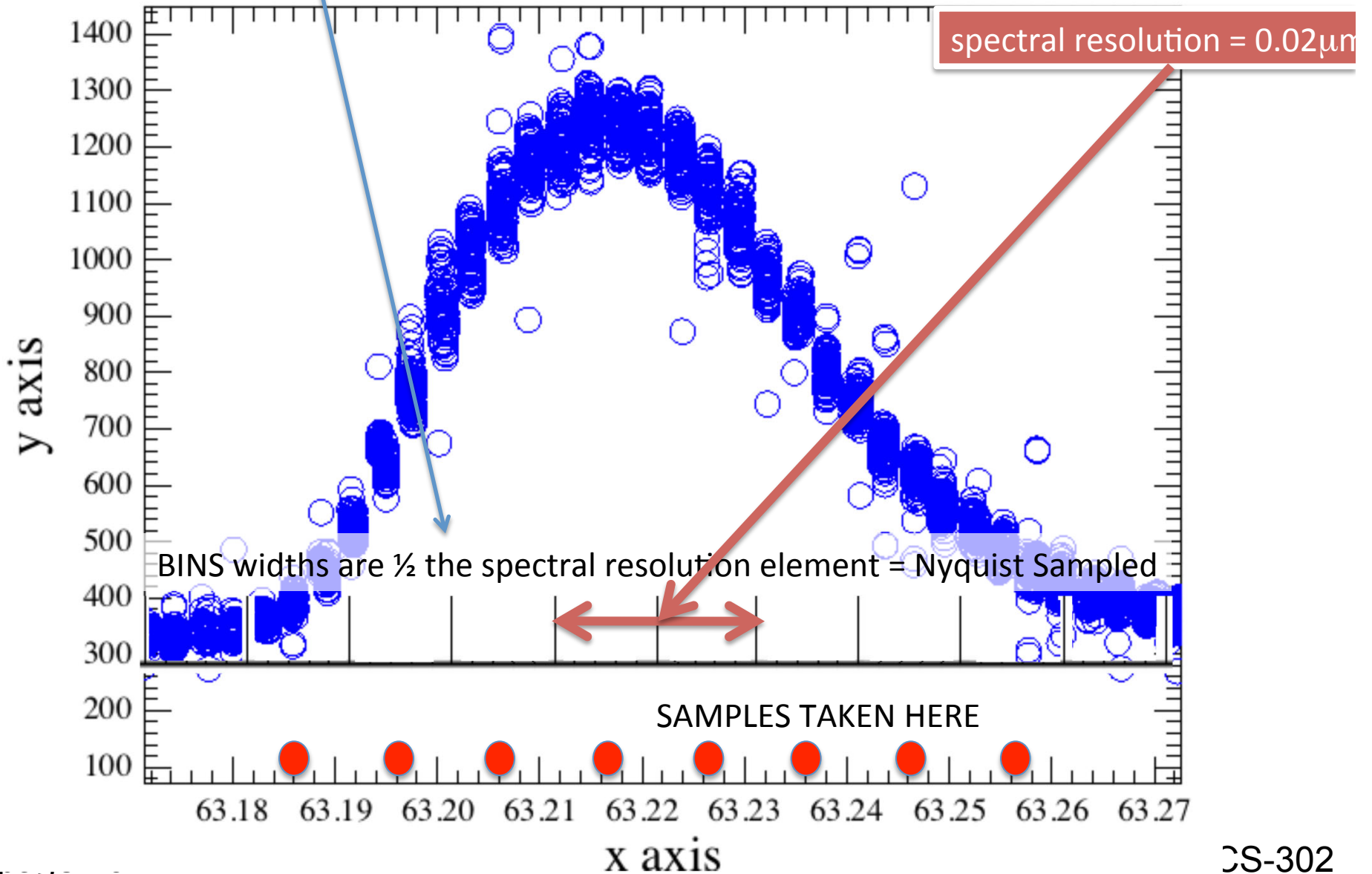
Illustrative examples follow....



# Examples of Oversample and Upsample Parameter Pairs



Oversample = 2 Upsample = 1  
bins =  $\frac{1}{2}$  spectral resolution  
at that wavelength

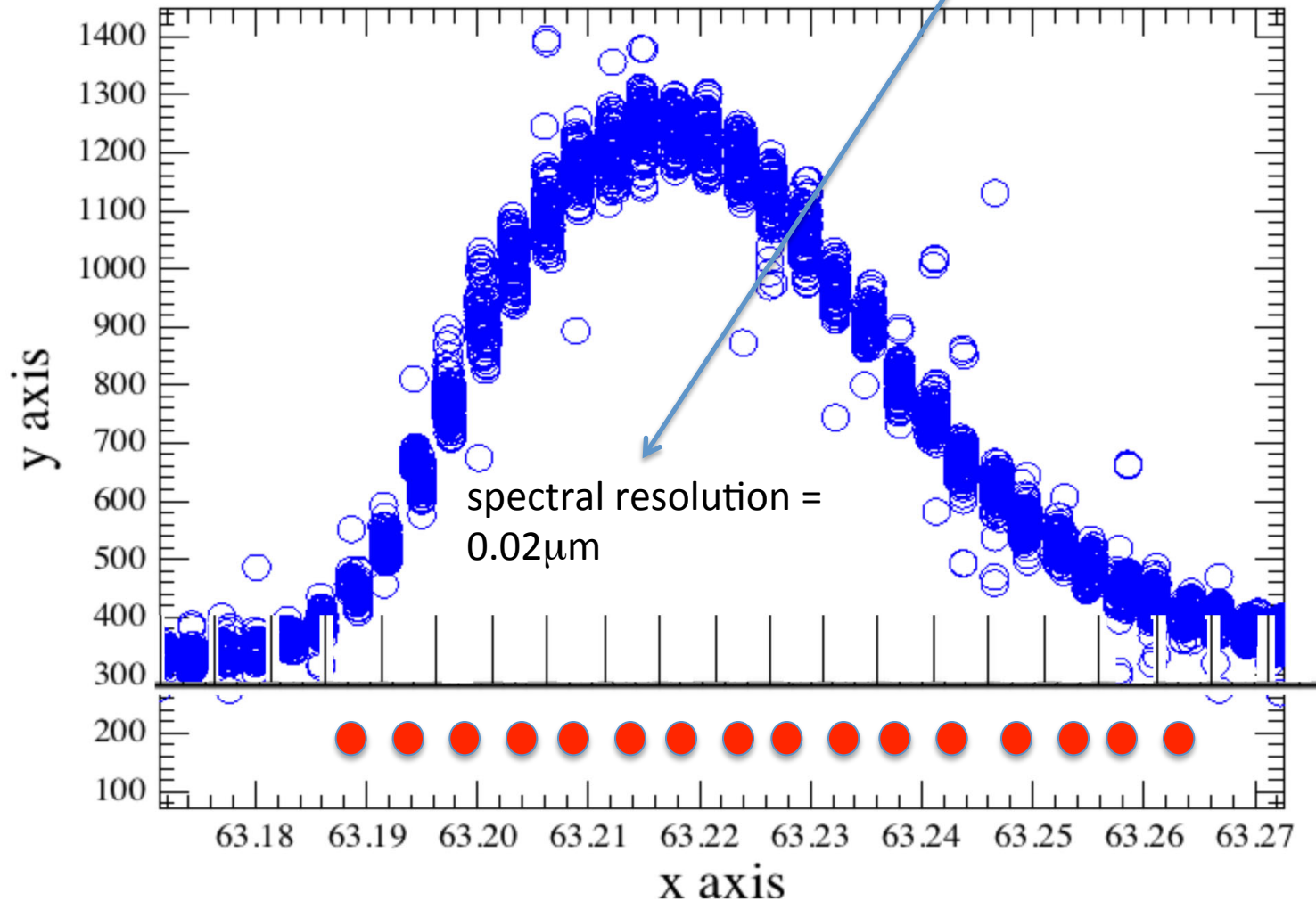




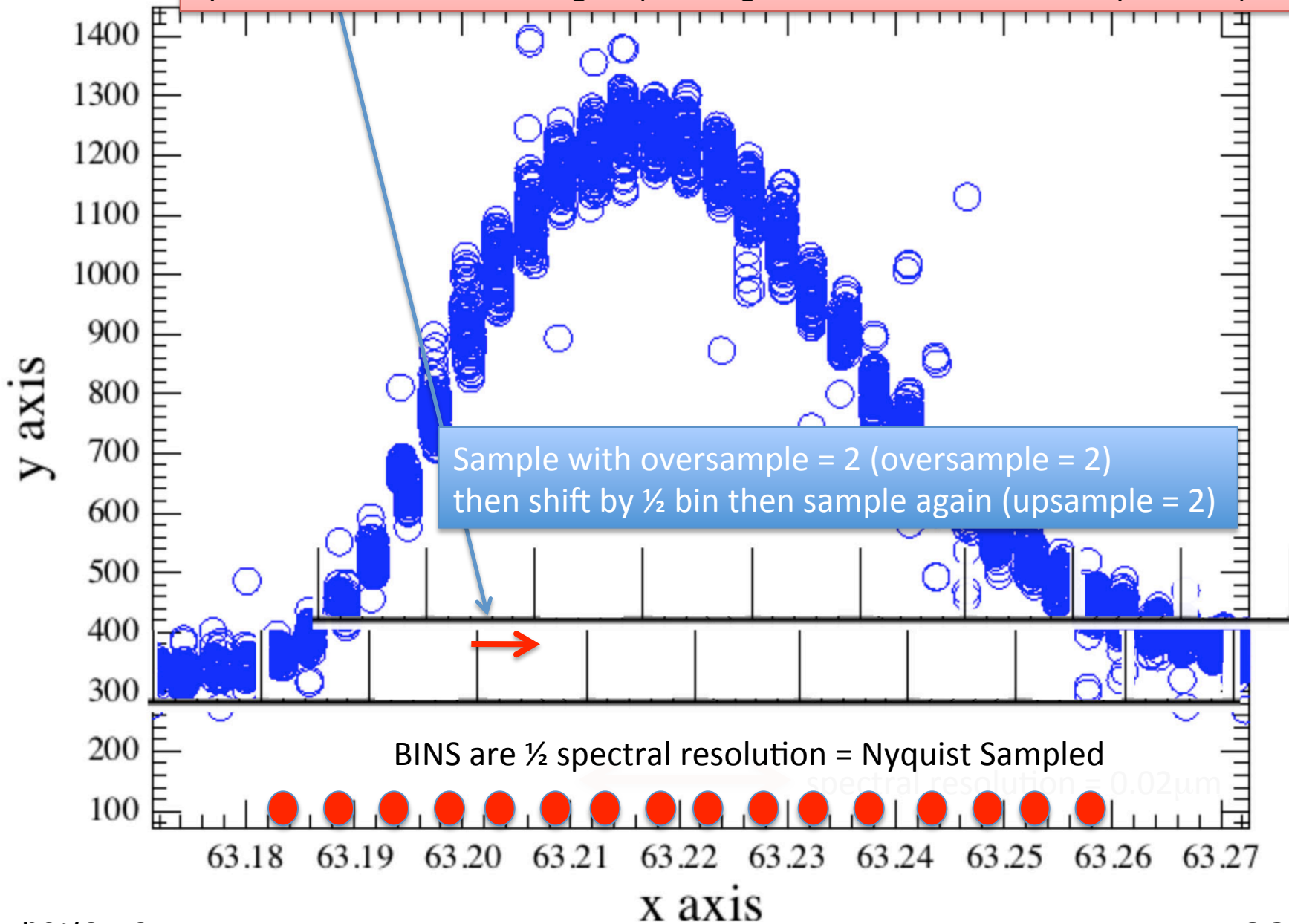


Oversample = 4, Upsample = 1  
bins = 1/4 spectral resolution  
at that wavelength

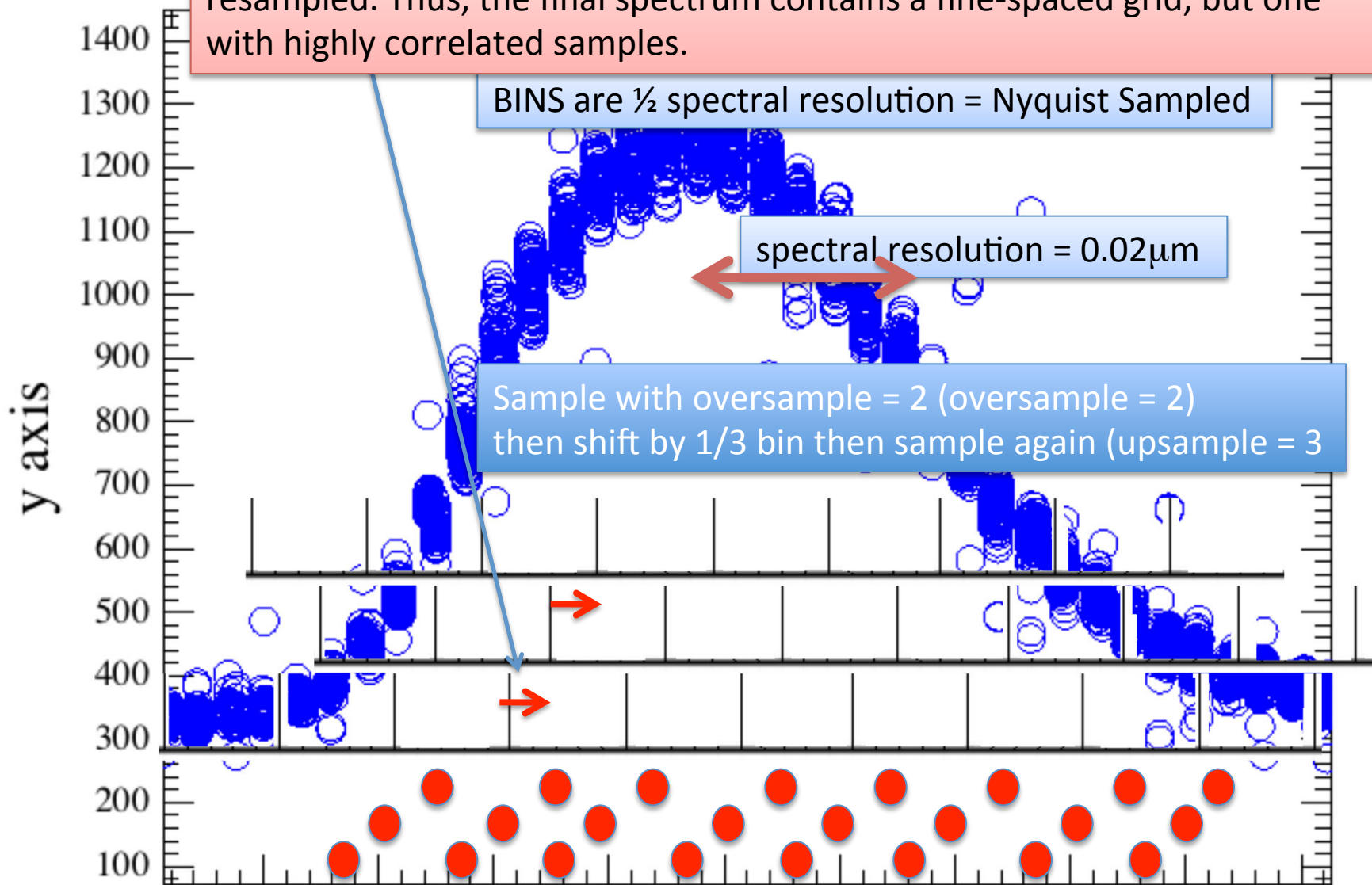
Oversample = 4 means  
4 times narrower bins than the  
spectral resolution (2 x better than Nyquist)



Oversample = 2 Upsample = 2 bins =  $\frac{1}{2}$  spectral resolution at that wavelength, but bins are shifted by  $\frac{1}{2}$  a bin and resampled, thus the final spectrum contains a finer grid (although the values are not independent).



Oversample = 2, Upsample = 3 ; Binwidths are  $\frac{1}{2}$  the spectral resolution at their wavelength, and bins are shifted by  $\frac{1}{3}$  and  $\frac{2}{3}$  of a binwidth and resampled. Thus, the final spectrum contains a fine-spaced grid, but one with highly correlated samples.



Sample centers are spaced at intervals  $\frac{1}{3}$  the binwidth.



## Step 3

Before regridding, we apply OUTLIERS rejection flagging to the spectra. This process is quite robust and is found to work well for PACS spectra. If the user suspects that the Deglitcher is over-flagging with GLITCH flags, the effect of these GLITCH flags can be turned-off and the de-glitching can instead be done with the OUTLIERS rejection flag method

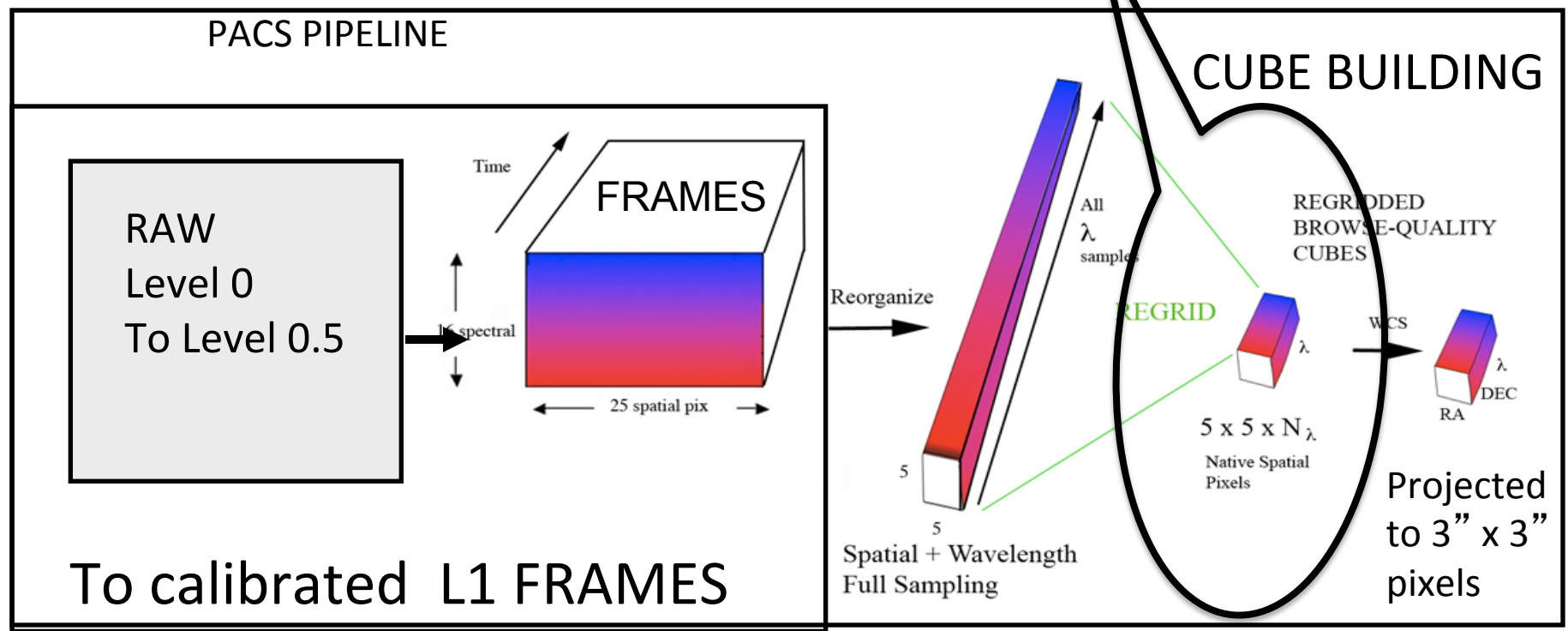
Next we active the masks and apply  
a sigma-clipping routine to the spectra  
(See PACS Data Reduction Guide: Spectroscopy, 5.2.8. for details)

```
# Activate all masks
slicedCubes = activateMasks(slicedCubes, String1d([str(i) for i in slicedCubes.get(0).maskTypes \
    if i not in ["INLINE", "OUTLIERS_B4FF"]]), exclusive = True)
# Flag the remaining outliers, (sigma-clipping in wavelength domain)
slicedCubes = specFlagOutliers(slicedCubes, waveGrid, nSigma=5, nIter=1)
```

specFlagOutliers has the task of defining a new flag called “OUTLIERS” created using a simple sigma-clip algorithm on each bin. nIter=1 means that the algorithm has been applied once and then again, iteratively rejecting points > nSigma. The user can experiment with these two parameters. The output of this routine is to create a mask. The mask is later applied when the actual rebinning of the spectra onto the waveGrid takes place. The mask is called “OUTLIERS” and is activated in the next step.

**NOTE ON EXCLUSION OF GLITCH MASK:** If you choose to exclude the glitch detection from your results, remove the “GLITCH” string from the activateMasks command above. This will ignore the glitch mask. We have had good results by doing this.

Now we will create our first set of rebinned cubes—one for each pacsCube: in our `lineId=2` case, we have six pacsCubes: i.e., for each repetition (we have three), one pacsCube for Nod A and one for Nod B



CALIBRATED FRAME      PACSCUBE CUBE      REBINNED CUBE      PROJECTED CUBE

Level 1      Level 2



# Step 4

Create the Rebinned Cube  
of dimensions 5 x 5 x rebinned wavelength  
elements



## Now Create the Rebinned Cube



We activate the OUTLIER mask for the first time. This happens before rebinning

```
# Activate all masks
slicedCubes = activateMasks(slicedCubes, String1d([str(i) for i in slicedCubes.get(0).maskTypes \
    if i not in ["INLINE", "OUTLIERS_B4FF"]]), exclusive = True)
# Rebin all selected cubes on the same wavelength (mandatory for specAddNod)
slicedRebinnedCubes = specWaveRebin(slicedCubes, waveGrid)
```

This step produces a set of rebinned cubes (one slice per cube)

**NOTE ON EXCLUSION OF GLITCH MASK:** If you choose to exclude the glitch detection from your results, add the “GLITCH” string to the activateMasks command above. This will ignore the glitch mask. We have had good results by doing this. This is the second and last time you need to worry about ignoring the glitch mask. If you performed this step and the one before specFlagOutliers then you will have a rebinned cube which excludes the glitch detection and relies on the sigmaClipping for removal of outliers. In general, we have found sigmaClipping to produce the better results.





# Step 4 (con' t)

## Average the Nods



Now we average together the two Nod positions. For an observation with a set of raster positions, there still will be more than one final cube (store as slices)—one for each raster position

```
# Average the nod-A & nod-B rebinned cubes.  
# All cubes at the same raster position are averaged.  
# This is the final science-grade product for single pointing and spatially undersampled  
# rasters.  
slicedFinalCubes = specAddNodCubes(slicedRebinnedCubes)
```



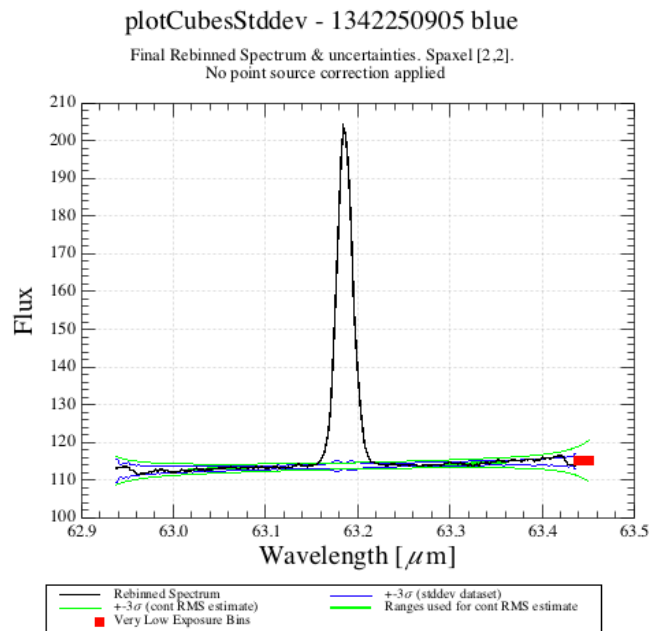
# Step 5

Inspect the rebinned spectra—spaxel by spaxel using various diagnostic tools

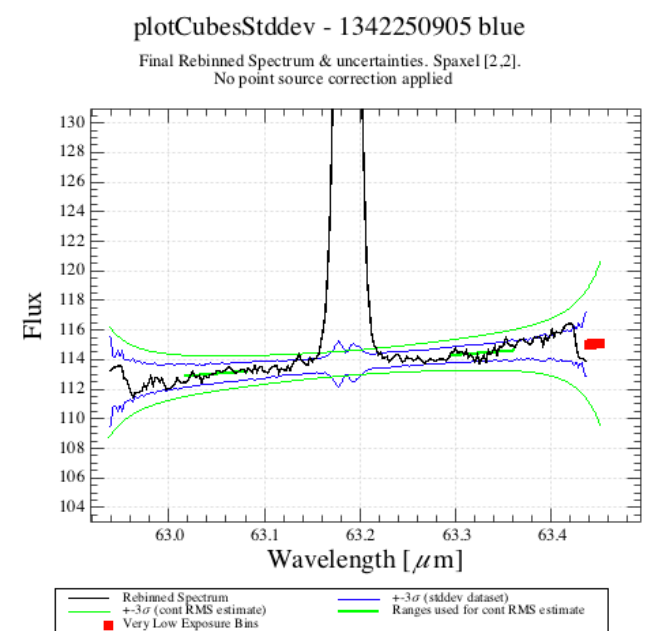
With the verbose=1 diagnostics, we can view (e.g.) the central (2,2) spaxel profile along with its estimated line flux and continuum RMS.

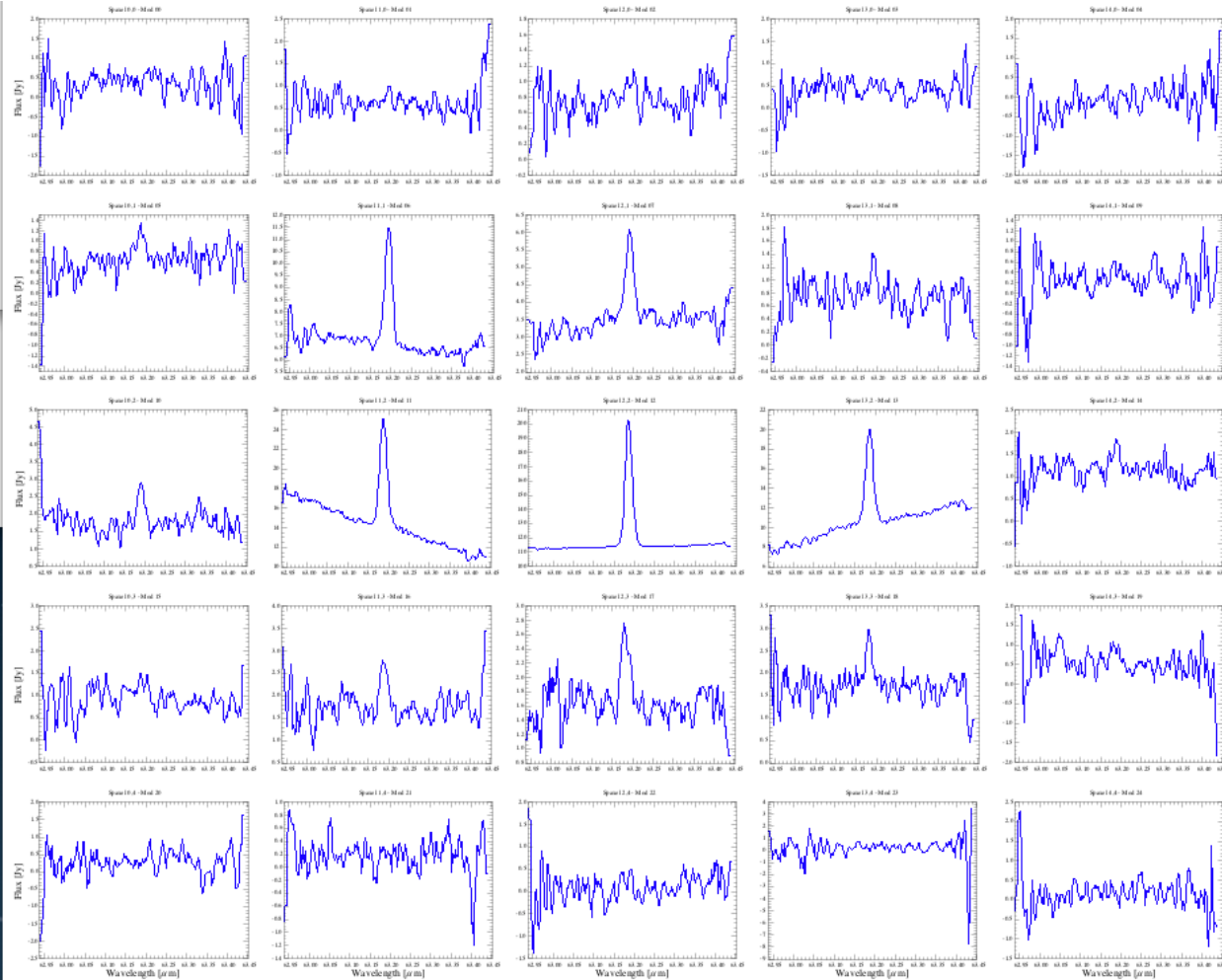
```

405 if verbose:
406     slicedSummary(slicedFinalCubes)
407     # Central spaxel for all raster positions
408     x,y = 2,2
409     pfinal = plotCubes(slicedFinalCubes, x=x, y=y,stroke=1,title="plotCubes - "+str(obsid)+" "+camera)
410     #
411     # Same as above, now overplotting an estimate of the continuum RMS
412     pstd = plotCubesStddev(slicedFinalCubes, plotLowExp=1, plotDev=0, nsigma=3, isLineScan=1, spaxel)
413     pstd.titleText, pstd.subtitleText="plotCubesStddev - "+str(obsid)+" "+camera,"Final Rebinned Spec
414     #
  
```



Draw a box to zoom in  
→





```

415 # 5x5 plot of one of the rebinned cubes (one line/range at one raster position)
416 slice = 0
417 p55 = plotCube5x5(slicedFinalCubes.get(slice), frameTitle="plotCube5x5 - "+str(o

```

In the case of a raster observation, you can plot the profiles for each slice separately.



# Step 6

## *(for point sources and single pointing)*

Extract spectra from the central spaxel



# Extracting the spectrum for Point Sources

**Caveats:** The following instructions assume that the observation consists of a single pointing of a target which is a point source\*, and that the target peak position is centered on the central spaxel [2,2] (i.e., the flux peaks at spaxel [2,2])\*\*.

\*If there are multiple pointings, these should be handled separately following the instructions below using the individual rebinned cubes. (The PACS point source corrections operate only on individual rebinned cubes.)

\*\*If the source is in a spaxel other than the central spaxel, use the “PACS Point Source Loss Correction (any spaxel)” script found in HIPE->Scripts->PACS useful scripts.

**extractCentralSpectrum** will return three spectra:

- a) Spectrum of the central pixel corrected for the part of the beam that the central spaxel misses. This is known as the **c1** spectrum.
- b) Spectrum of the sum of the central 9 pixels, with the (much smaller) correction for the part of the beam that this “superspaxel” misses: the **c9** spectrum.
- c) Spectrum of the central pixel, with the “3x3” correction that compares the ratio of **c1** to **c9** to the ratio expected from the beam profile; this is intended to correct for small mis-pointings and is the **c129** spectrum (‘c one-to-nine’, get it?). To trust this correction the source continuum must be of order 10 Jy.

Discussions of these corrections are found in the PACS Data Reduction Guide: Spectroscopy section 8.3 and 8.4.



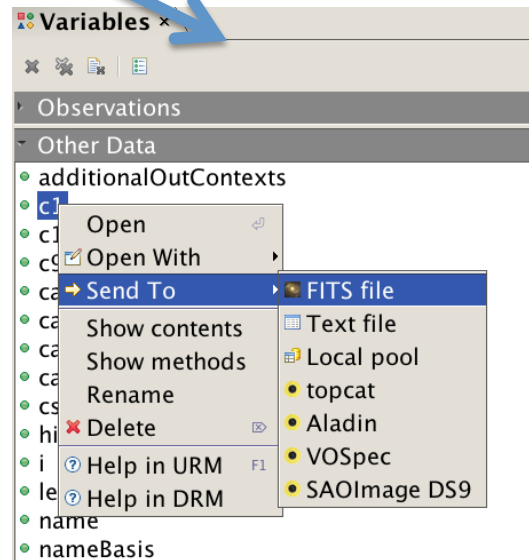
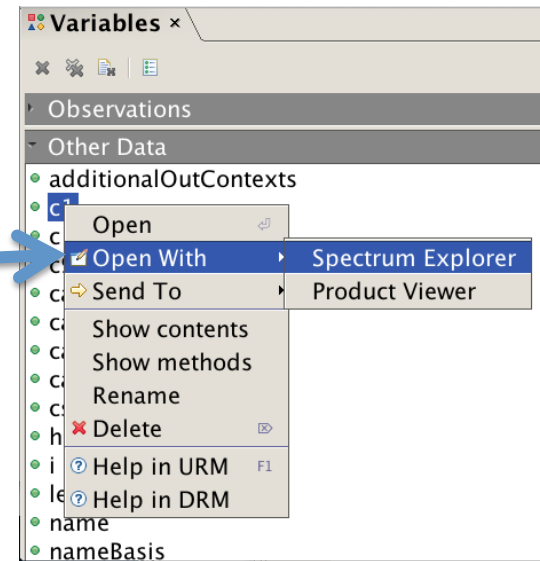
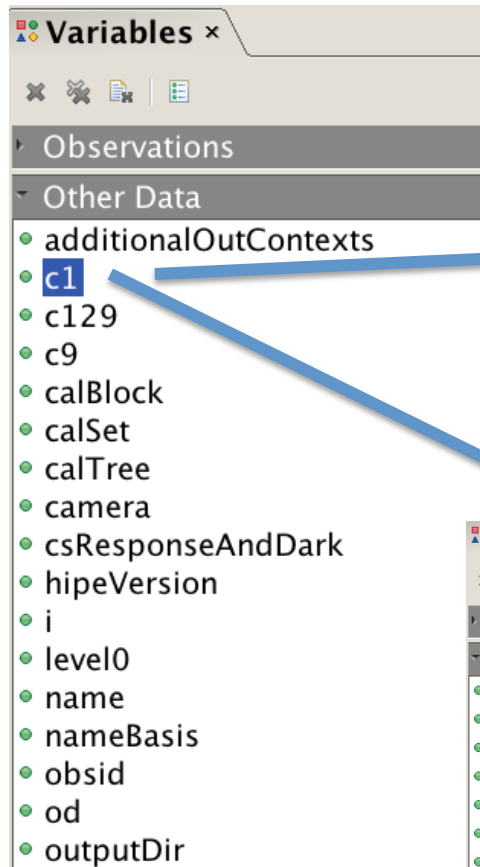
## Extracting the spectrum for Point Sources (con't)

```
for slice in range(len(slicedFinalCubes.refs)):
    if verbose: print
    # a. Extract central spectrum, incl. point source correction (c1)
    # b. Extract SUM(central_3x3 spaxels), incl. point source correction (c9)
    # c. Scale central spaxel to the level of the central_3x3 (c129 -> See PDRG & print
        extractCentralSpectrum.__doc__)
    c1,c9,c129 = extractCentralSpectrum(slicedFinalCubes, slice=slice, smoothing='median', isLineScan=-1,
        calTree=calTree, verbose=verbose)
    #
    # Save to Fits
    if saveOutput:
        name = nameBasis + "_centralSpaxel_PointSourceCorrected_Corrected3x3NO_slice_"
        simpleFitsWriter(product=c1,file = outputDir + name + str(slice).zfill(2)+".fits")
        name = nameBasis + "_central9Spaxels_PointSourceCorrected_slice_"
        simpleFitsWriter(product=c9,file = outputDir + name + str(slice).zfill(2)+".fits")
        name = nameBasis + "_centralSpaxel_PointSourceCorrected_Corrected3x3YES_slice_"
        simpleFitsWriter(product=c129,file = outputDir + name + str(slice).zfill(2)+".fits")
```

On the next page we show how this can found in the variable list and opened in SpectrumExplorer.

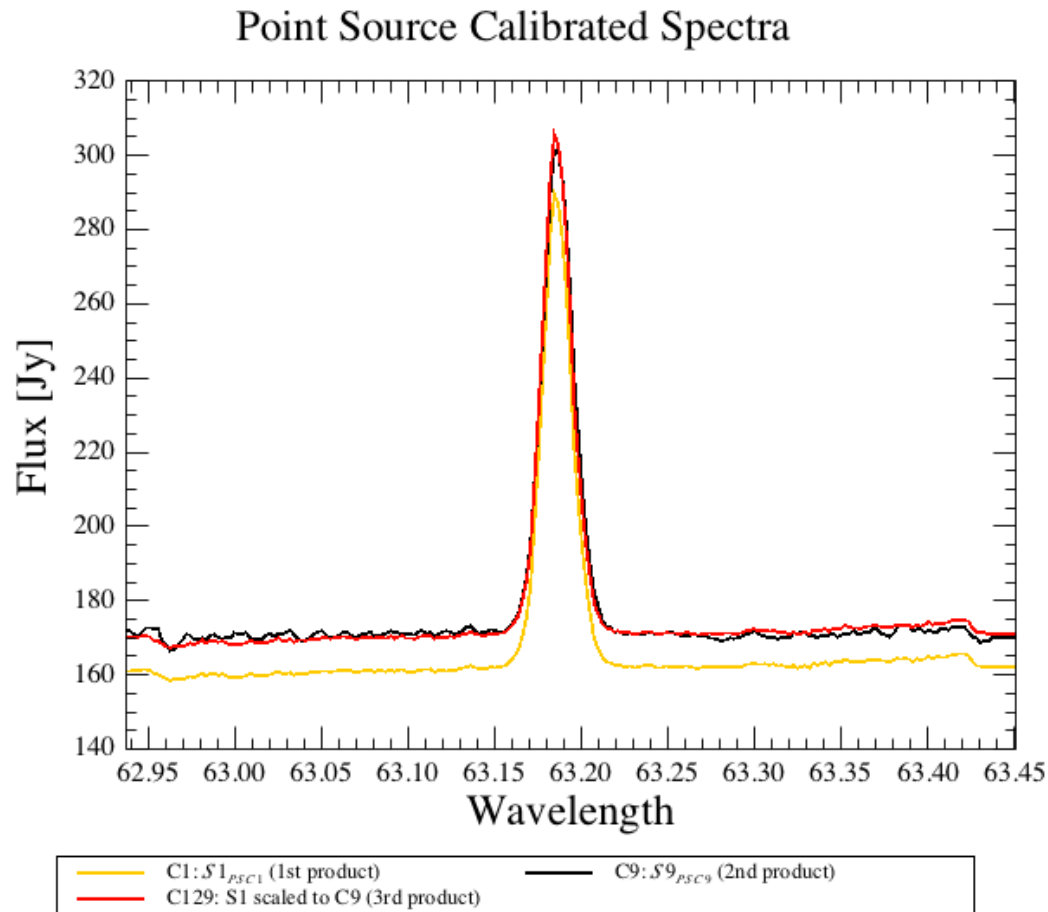


# Extracting the spectrum for Point Sources (con't)



In the variable list right-click on, e.g., c1 and either “open with” Spectrum Explorer or send to a FITS file

By executing the command lines on page 32,  
we get.....





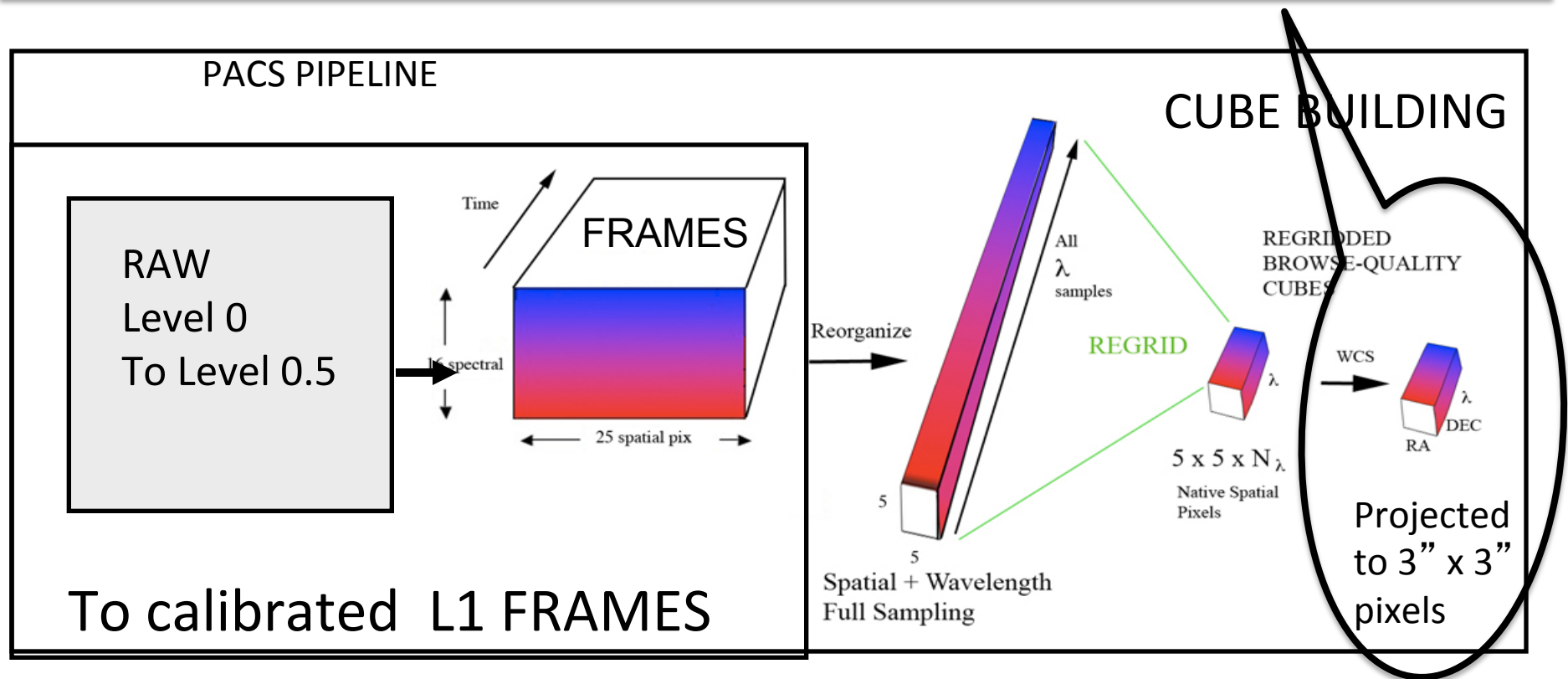
# Step 6

## *(for Raster Observations of Extended Sources)*

In order to mosaic your cubes onto a uniform World Coordinate System (WCS) grid, users with raster observations\* should select between the three methods of mosaicking: 1) “specProject” or 2) “Drizzling”, for oversampled maps; 3) “specInterpolate”, for undersampled maps.

\*As opposed to the single-pointing example data set of this tutorial

The projected cube is only recommended for raster observations where you have many rebinned cubes and these are combined into a final projected cube



CALIBRATED  
FRAME

PACSCUBE  
CUBE

REBINNED  
CUBE

PROJECTED  
CUBE

Level 1

Level 2 PACS-302

<http://nhsc.ipac.caltech.edu/helpdesk/index.php>



# specProject

(Refer to section 7.8 of the “PACS Data Reduction Guide for Spectroscopy”). For its relative speed, specProject is recommended for large wavelength range observations and SEDS. Each output spaxel is formed from a weighted combination of overlapping and/or undersampled spaxels from the slicedFinalCubes (which have been rebinned in wavelength) for each spatial and wavelength point onto a (default) 3” grid.



## Invoking specProject

```
# specProject works on the final rebinned cubes.  
slicedProjectedCubes = specProject(slicedFinalCubes,outputPixelSize=3.0)
```

```
# Display the projected cube in the Spectrum Explorer  
if verbose:  
    slice = 0  
    oneProjectedSlice = slicedProjectedCubes.refs[slice].product  
    openVariable("oneProjectedSlice", "Spectrum Explorer")
```

The present script makes a slicedProjectedCube and even opens up a slice in Spectrum Explorer. Also available are other viewers (by right-clicking on the variable "slicedProjectedCube") as well as the same FITS writing capability as earlier described.



Caveat: Making a projected cube from a single pointing

Making a projected cube (using specProject or Drizzling) from a single pointing is not recommended, but it is also not prohibited. However, the formal final product from a single pointing is considered to be a rebinned cube, not any projected cube. One may attempt to project a single pointing for visualization purposes (such as is done in this tutorial), but, because the PACS IFU footprints are distorted, flux conservation is typically not maintained in the output map.

Only in the case of a fully sampled raster (spatial dithered mapping) can one expect to recover proper fluxes from a projected cube.



# Drizzling

The Drizzling projection is so-called because the total “drops” of flux collected by the input pixels are divided into smaller “droplets” and then collected/weighted into the output pixels. It differs from specProject in that it operates on the Level 1 slicedPacsCubes prior to wavelength rebinning (not Level 2 cubes).

(Primary drizzle document: <http://www.stsci.edu/ftp/science/hdf/combination/drizzle.html>)





## Invoking Drizzling

For parameter details, refer to section 7.7 of the PACS Data Reduction Guide (Spectroscopy)

```
# Drizzling works from the not-rebinned cubes
oversampleWave = 2
upsampleWave   = 3
waveGrid       = wavelengthGrid(slicedCubes, oversample=oversampleWave,
                                upsample=upsampleWave, calTree = calTree)
oversampleSpace = 3
upsampleSpace   = 2
pixFrac         = 0.6
spaceGrid       = spatialGrid(slicedCubes, wavelengthGrid=waveGrid,
                              oversample=oversampleSpace, upsample=upsampleSpace,
                              pixfrac=pixFrac, calTree=calTree)
slicedDrizzledCubes = drizzle(slicedCubes, wavelengthGrid=waveGrid,
                              spatialGrid=spaceGrid)[0]
```

These Drizzled Cubes may be viewed in Spectrum Explorer as well.



## Invoking Drizzling (WARNING)

Warning: In Pipeline 13 – DRIZZLING is run by default – that is – the drizzling script lines shown in the previous slide are **not commented-out**.

The user should be sure that he/she wants to run drizzle before invoking it.

The drizzle routine is an excellent optimized and powerful projection method (when sufficient oversampling has been obtained within the observation) but it can require many hours of execution time and large amounts of computer memory, especially for large maps or line ranges. It is best run on a large and perhaps remote virtual machine (via a VNC session) and utilizing multi-threading.

The user's alternative, specProject will, in general, yield a fairly good projected map in much shorter processing times.



# specInterpolate

For undersampled raster maps or single pointing maps of extended sources, the best projection option is “specInterpolate”, which is based on Delaunay triangulation. In this projection, the default output pixel size is 4.7”.



## Invoking specInterpolate

For parameter details, refer to section 7.9 of the PACS Data Reduction Guide (Spectroscopy)

```
# The final science grade products are the previously produced #"slicedFinalCubes"  
# You can also interpolate these cubes on a regular spatial grid using  
# specInterpolate
```

```
outputPixelSize = 4.7  
slicedInterpolatedCubes = specInterpolate(slicedFinalCubes,  
outputPixelSize=outputPixelSize, conserveFlux=True)
```

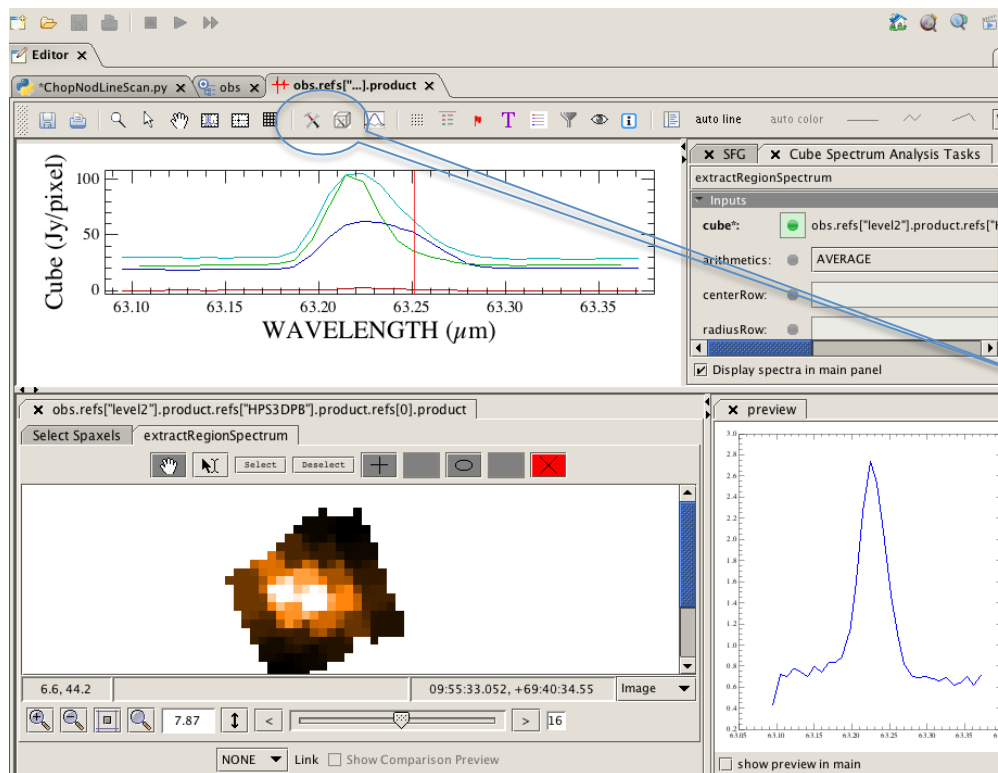
```
if saveOutput:  
    name = nameBasis+"_slicedInterpolatedCubes"  
    saveSlicedCopy(slicedInterpolatedCubes, name, poolLocation=outputDir)
```



# Step 7

Explore your final projected or rebinned  
cube with the Spectrum Explorer

# The Spectrum Explorer provides many visualization options as well as line fitting



You may display and examine the final spectral cubes with the Spectrum Explorer.

Further processing can be performed in this environment using, e.g., the Cube Tool Box and the Spectrum Fitter GUI. These allow line extraction in a selected area, baseline fitting, the generation of integrated line maps, etc..

# Useful Scripts are provided for making integrated line maps, and for extracting point source spectra from spaxels other than the central one

For the case shown in this tutorial (single pointing), use the last script in the pulldown menu, that operates on the rebinned cubes.

For well-sampled raster maps, use “Fitting and making fit-images, Level 2 projected/drizzled cubes”.

