GMOS Data Reduction

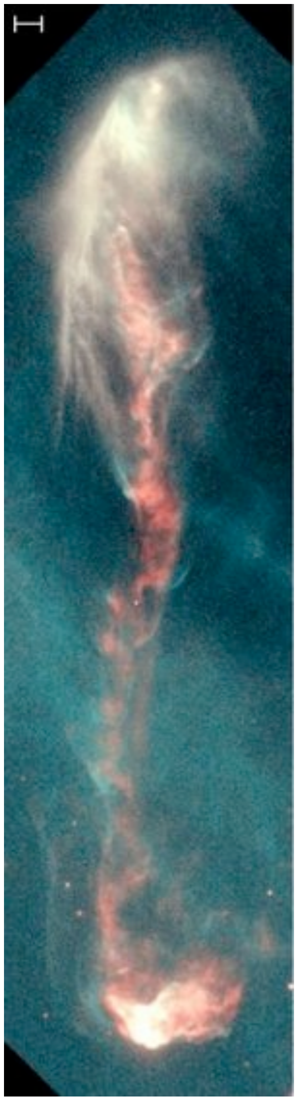
Richard McDermid

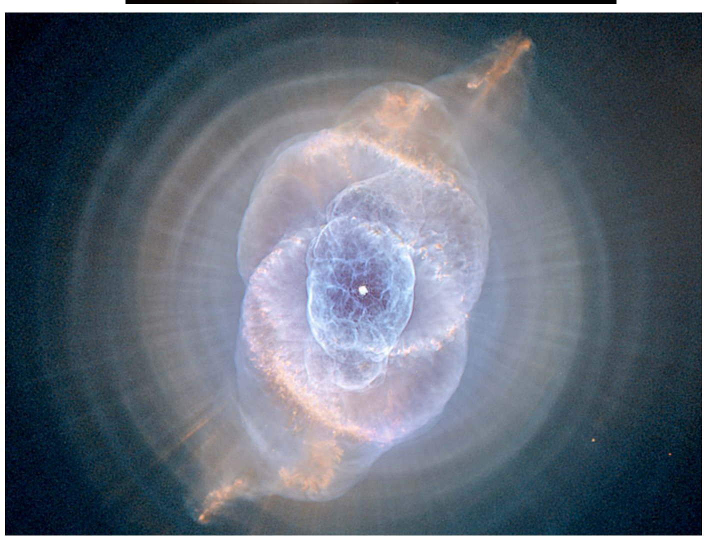
Gemini Data Reduction Workshop

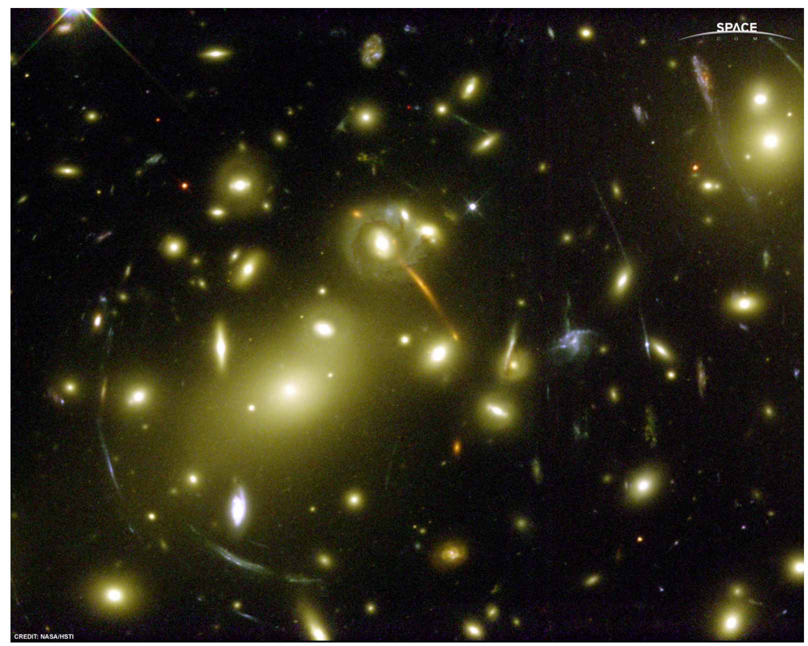
Tucson, July 2010

Motivation for IFUs

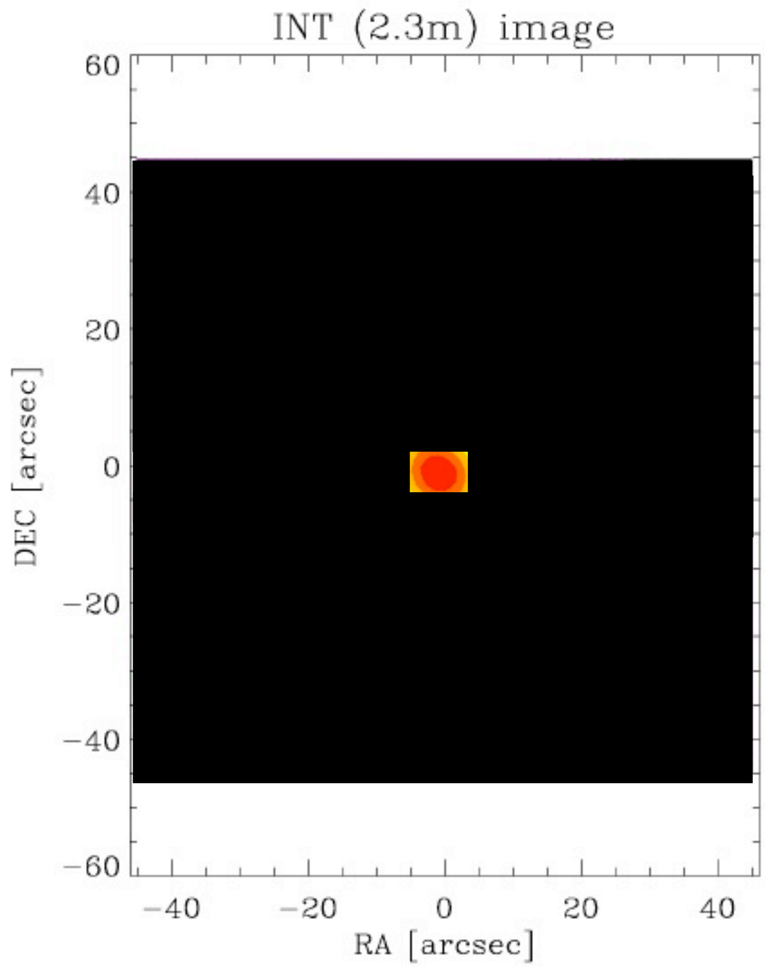
- Many objects appear extended on the sky

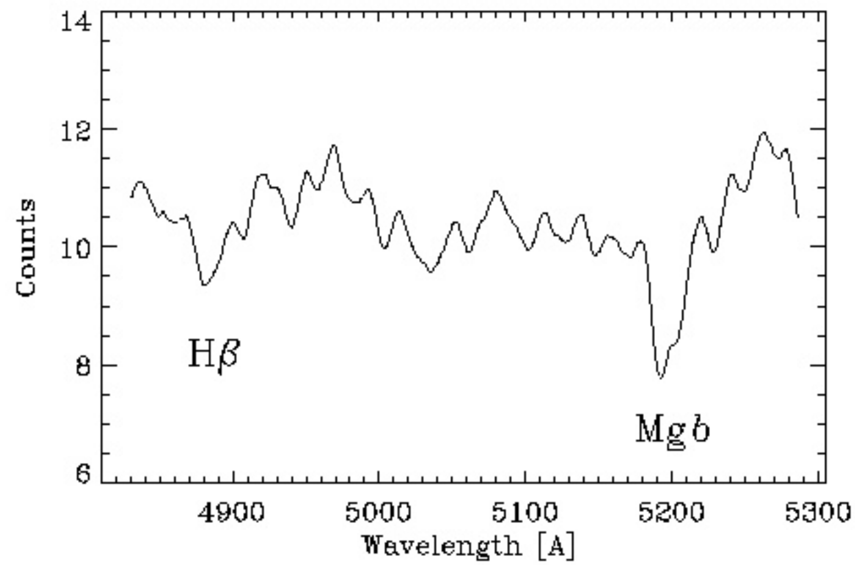






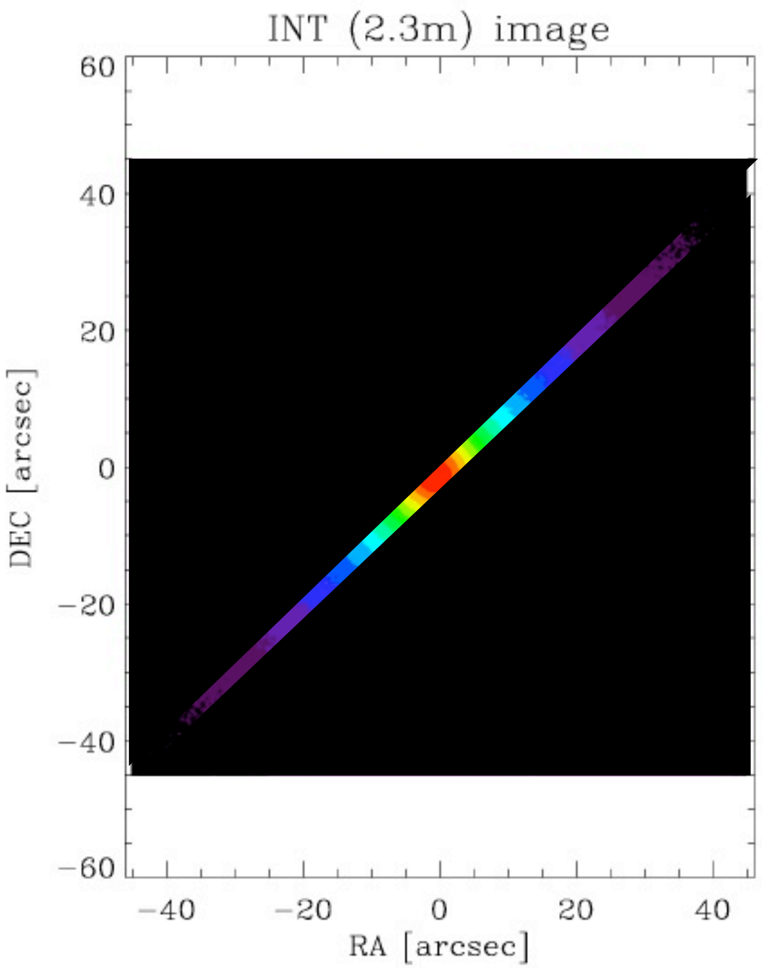
Aperture spectroscopy

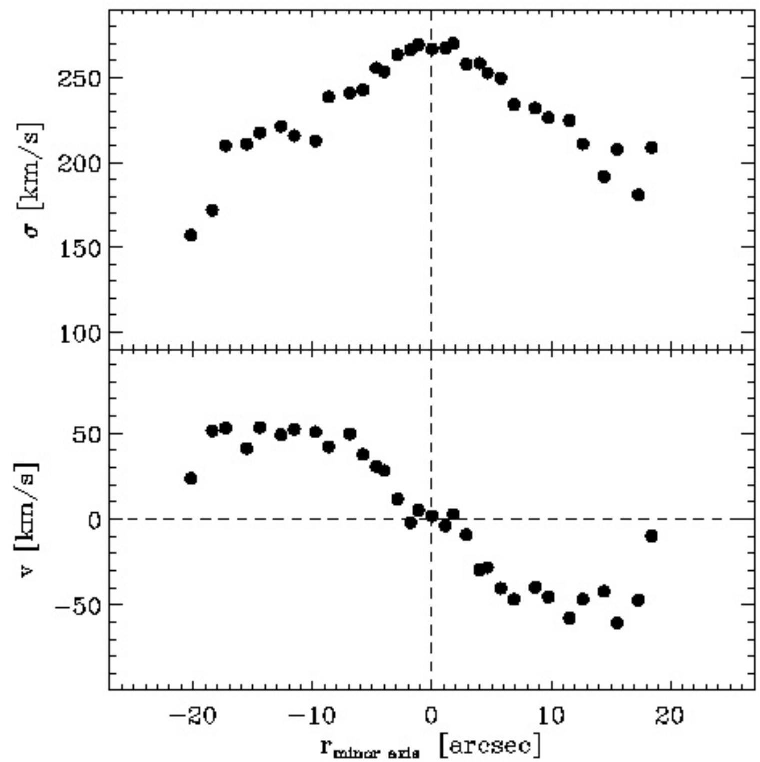




Central velocity,
dispersion, line-strength

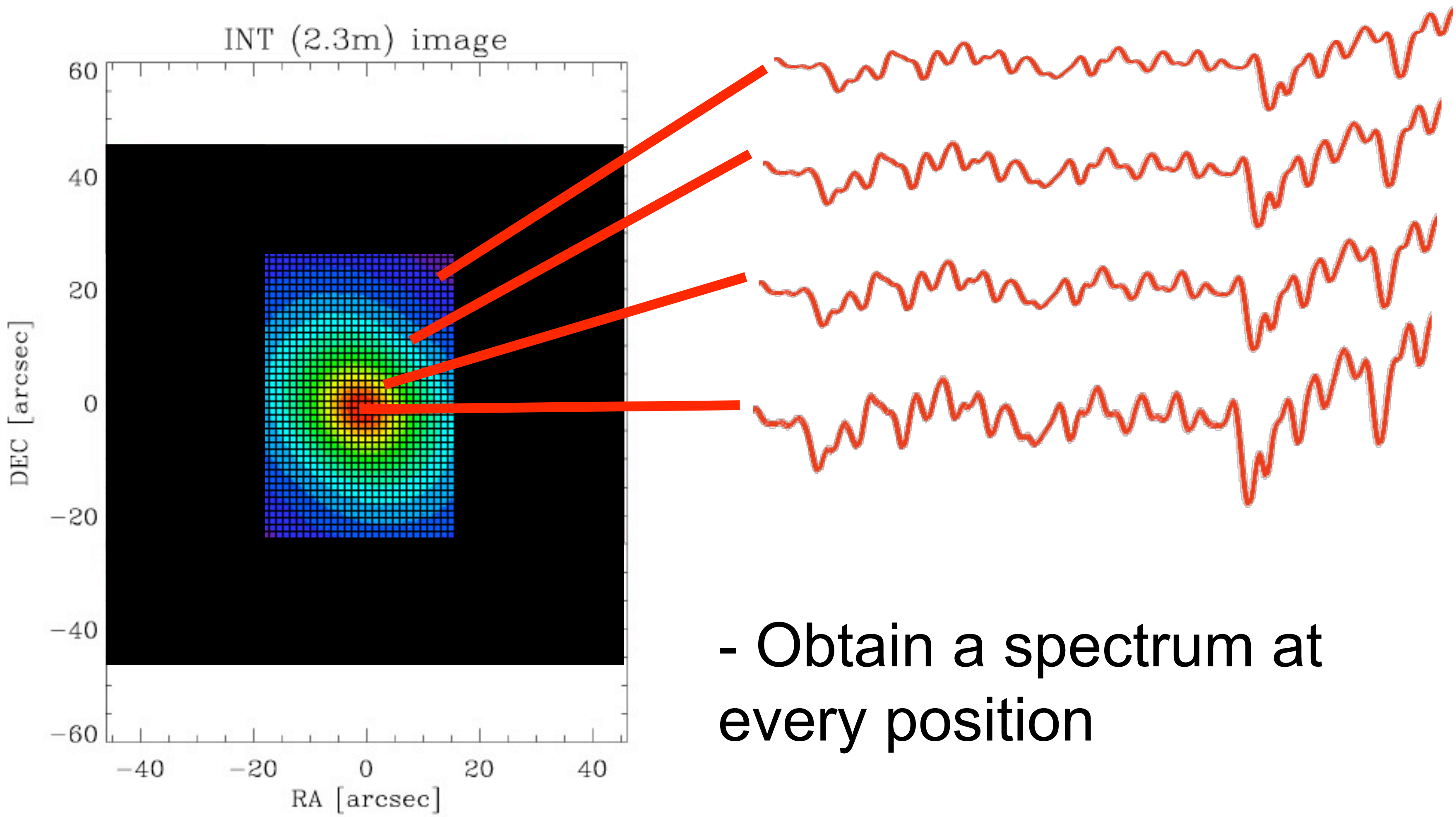
Longslit spectroscopy





Also line-strength

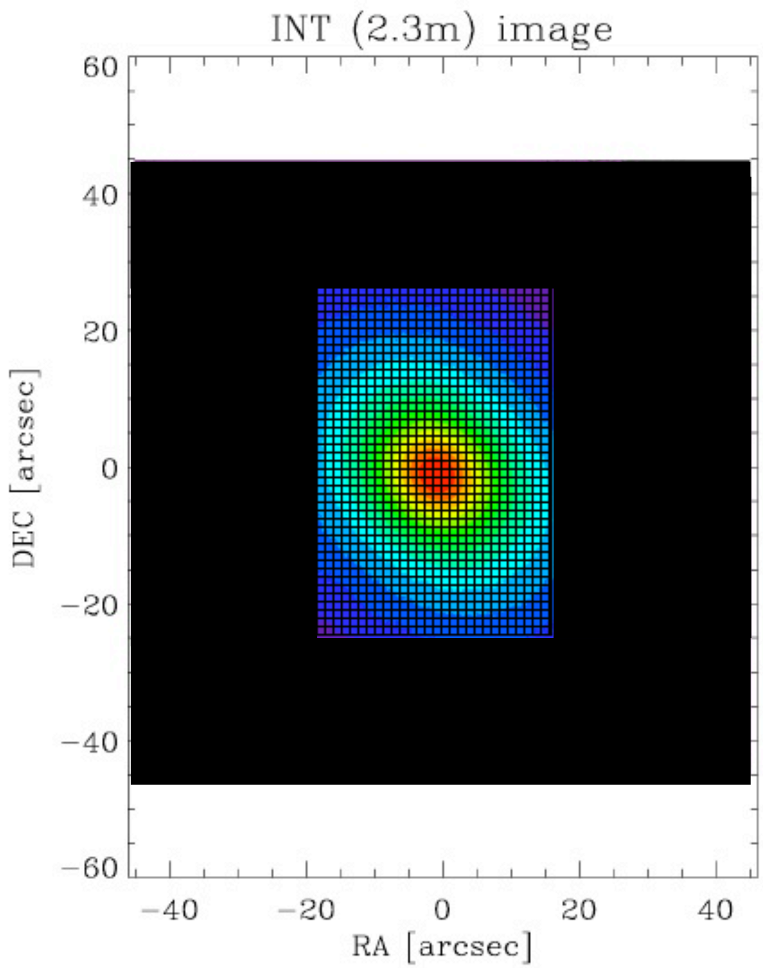
Integral-Field spectroscopy

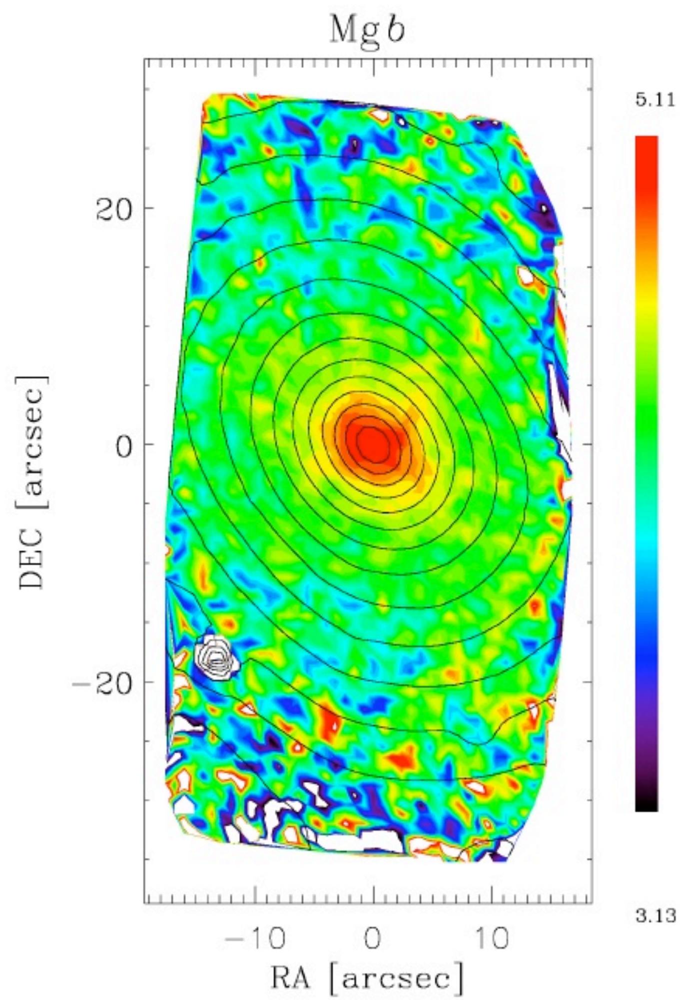


- Obtain a spectrum at every position

Integral-Field spectroscopy

And each spectrum gives:



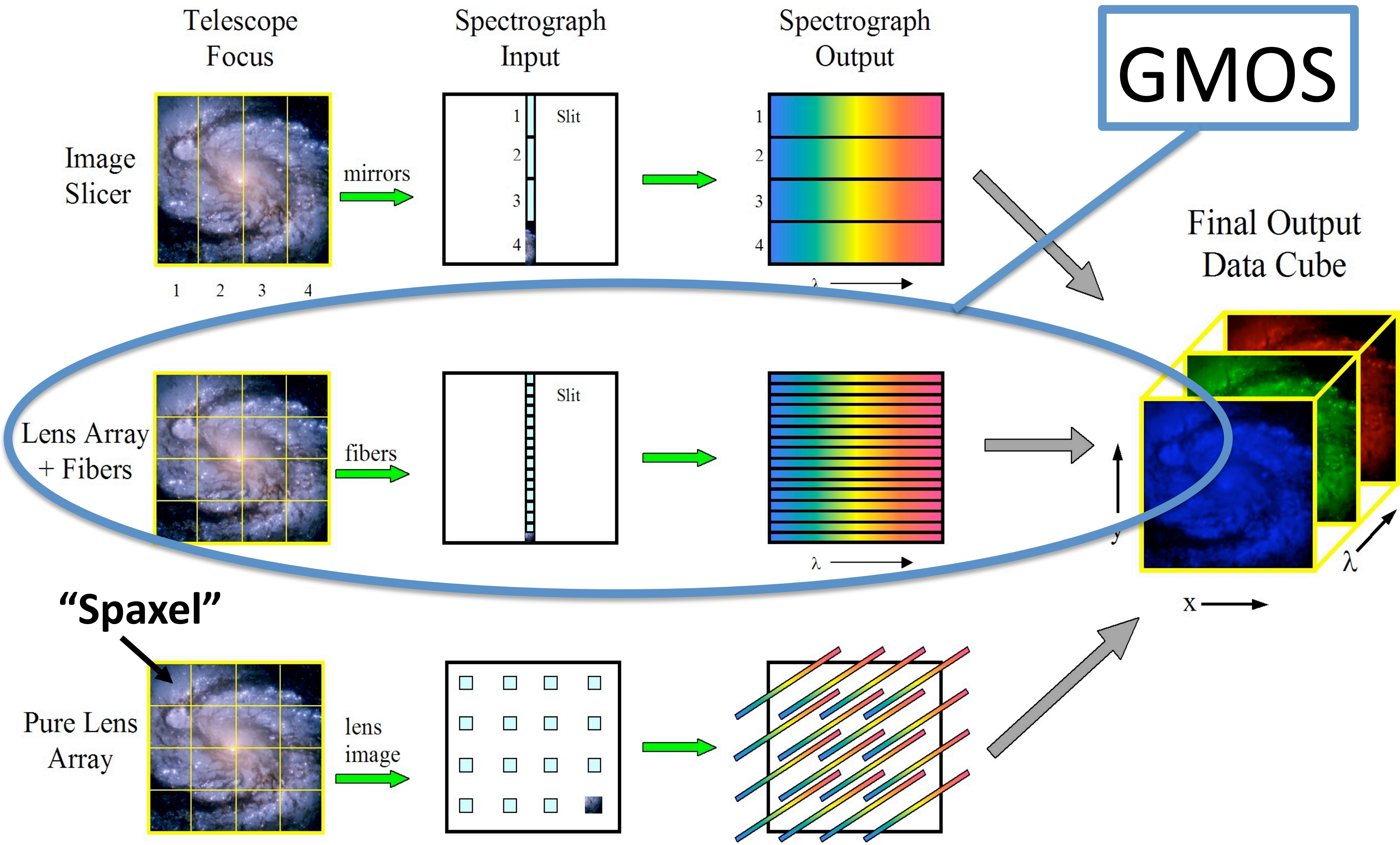


LINE STRENGTHS

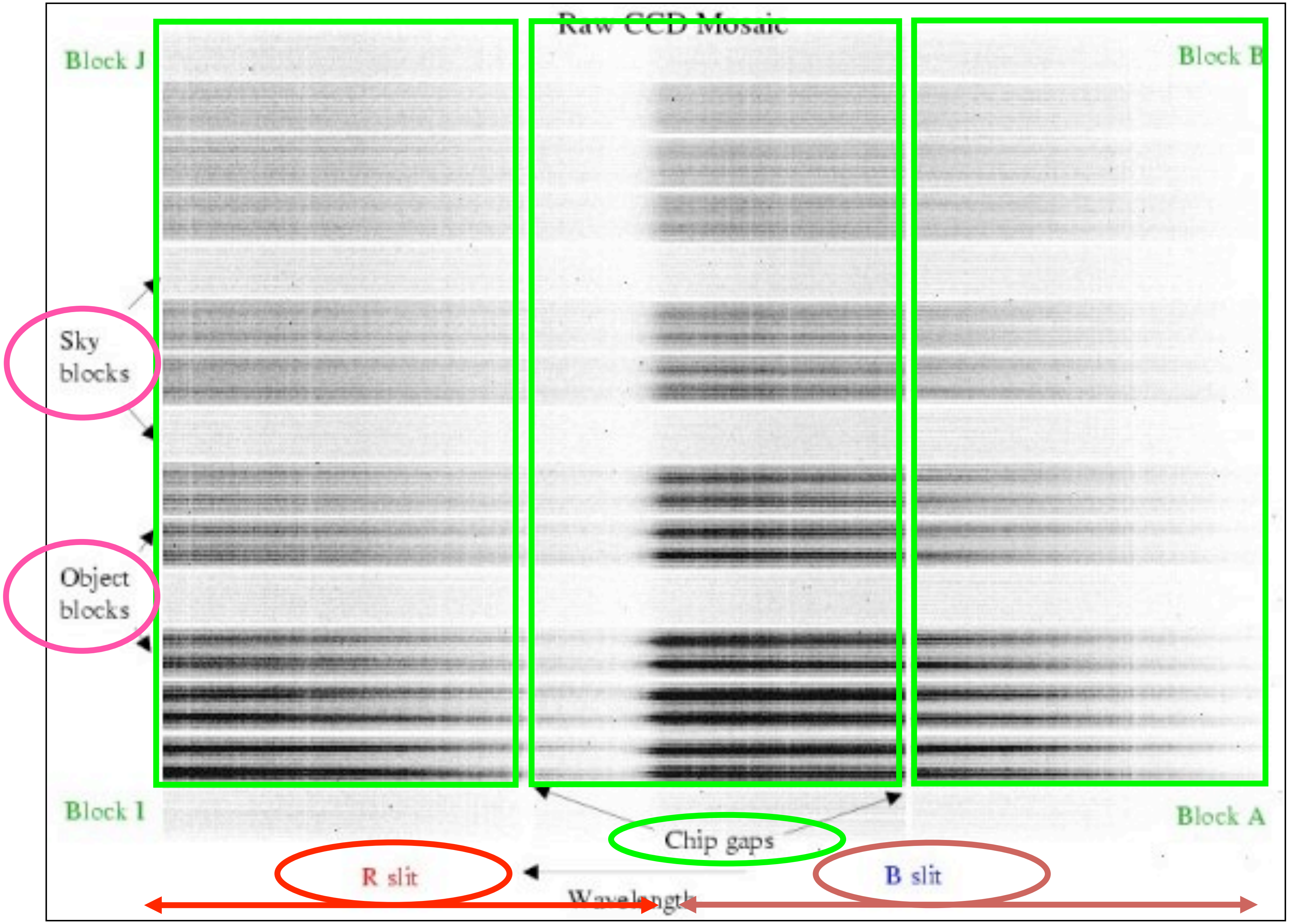
GMOS

- Optical Integral Field Spectrograph
- Lenslet-fiber based design
- Various spectral capabilities
- Two spatial settings:
  - ‘Two-slit’:
    - 5”x7” FoV
    - 3,000 spectral pixels
    - 1500 spectra (inc. 500 sky)
  - ‘One-slit’:
    - 2.5”x3.5”
    - 6,000 spectral pixels
    - 750 spectra (inc. 250 sky)
  - Both modes have same spatial sampling of ~0.2” per fiber
- Dedicated sky fibers 60” offset for simultaneous sky

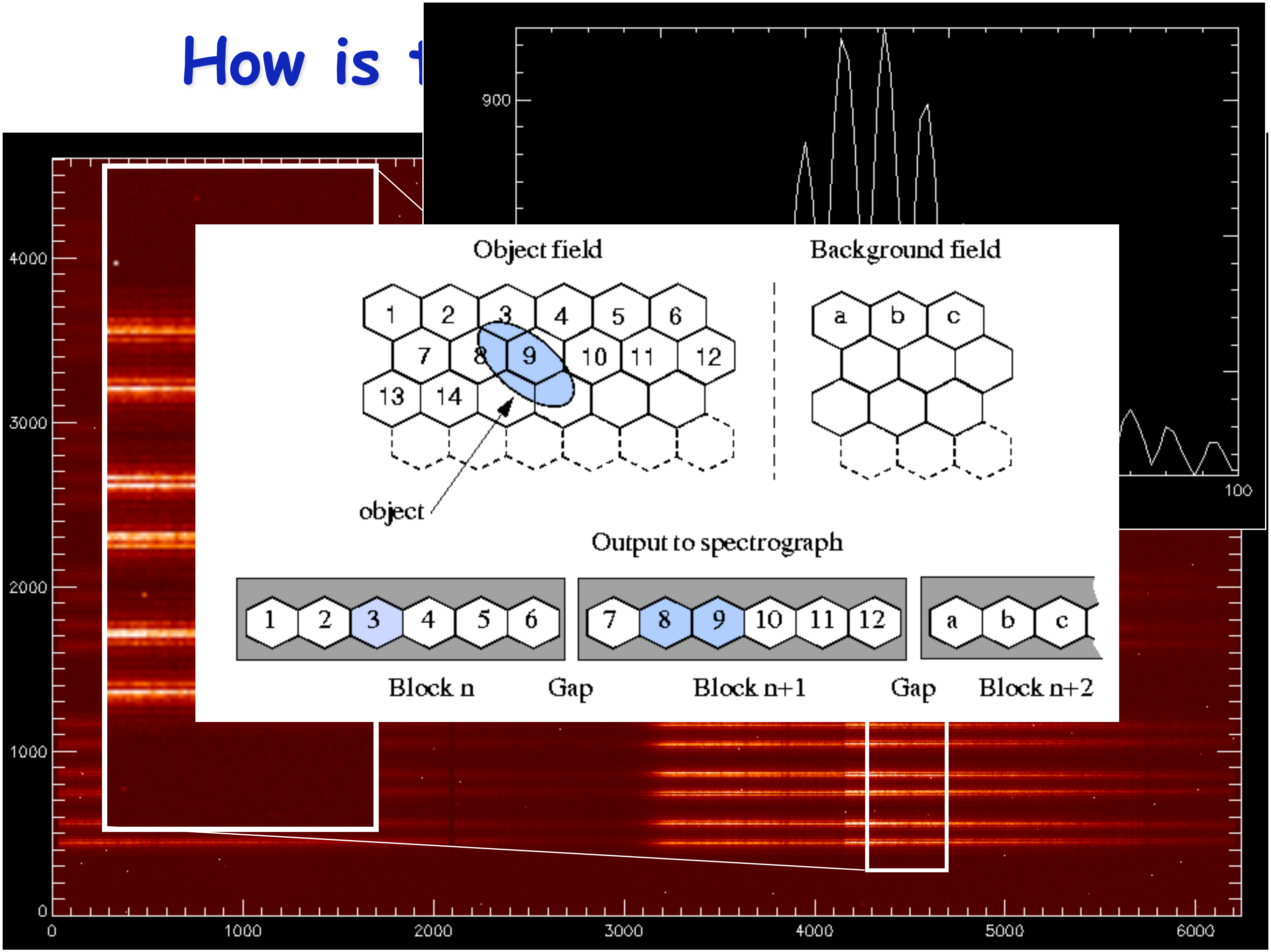
IFU Zoo: How to map 3D on 2D



GMOS Example: M32



How is t



900
100
4000
3000
2000
1000
0
0
1000
2000
3000
4000
5000
6000
Object field
Background field
1
2
3
4
5
6
7
8
9
10
11
12
13
14
a
b
c
object
Output to spectrograph
Block n
Gap
Block n+1
Gap
Block n+2

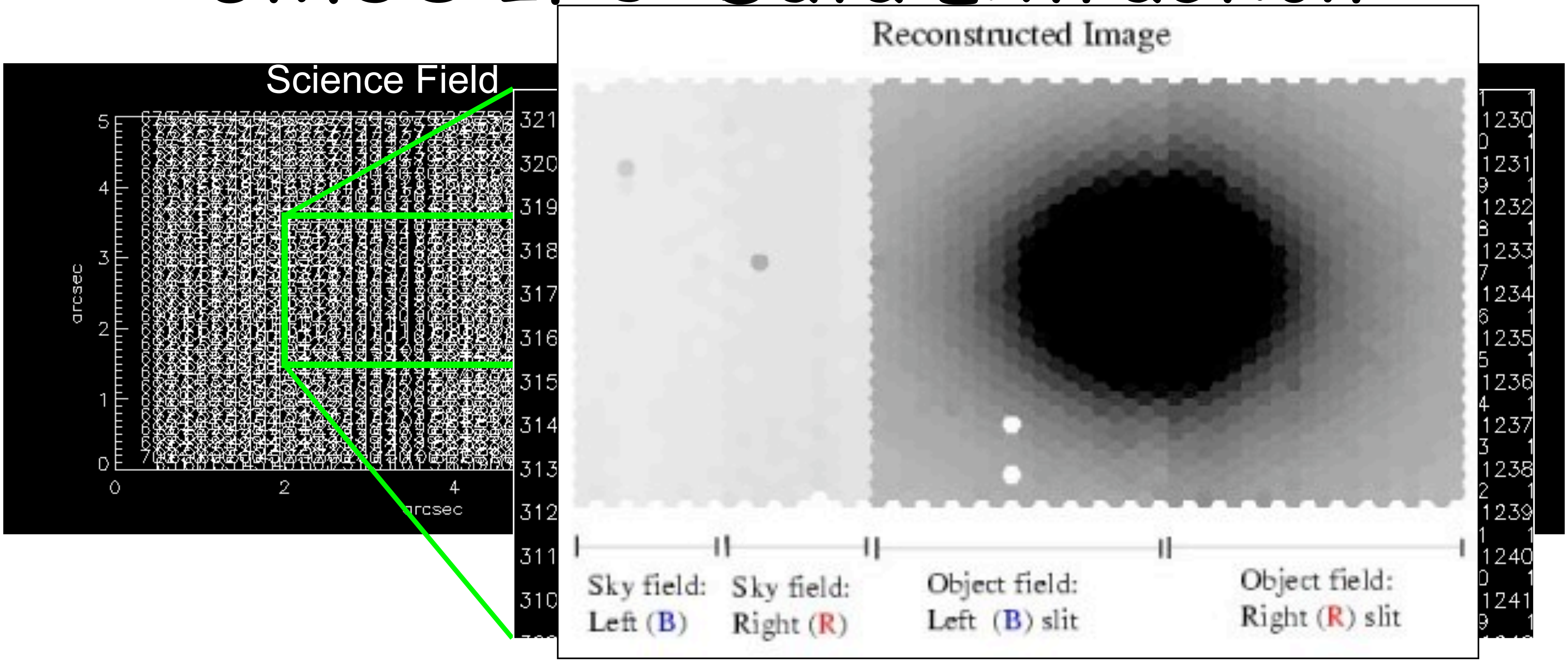
GMOS IFU: Data Extraction

gnifu_slits_mdf.fits

Select (All, Invert)	NO 1J	XINST 1E	YINST 1E	BLOCK 5A	BEAM 1J
1	1	62.252	0.000	I_1	-1
2	2	62.252	0.200	I_2	1
3	3	62.252	0.400	I_3	1
4	4	62.252	0.600	I_4	1
5	5	62.252	0.800	I_5	1
6	6	62.252	1.000	I_6	1
7	7	62.252	1.200	I_7	1
8	8	62.252	1.400	I_8	1
9	9	62.252	1.600	I_9	1
10	10	62.252	1.800	I_10	1

- Mask Definition File (MDF) provides sky coordinates of each fibre on CCD
- Together with wavelength calibration, provide translation from CCD (x,y) to data-cube (RA,Dec,λ)

GMOS IFU: Data Extraction

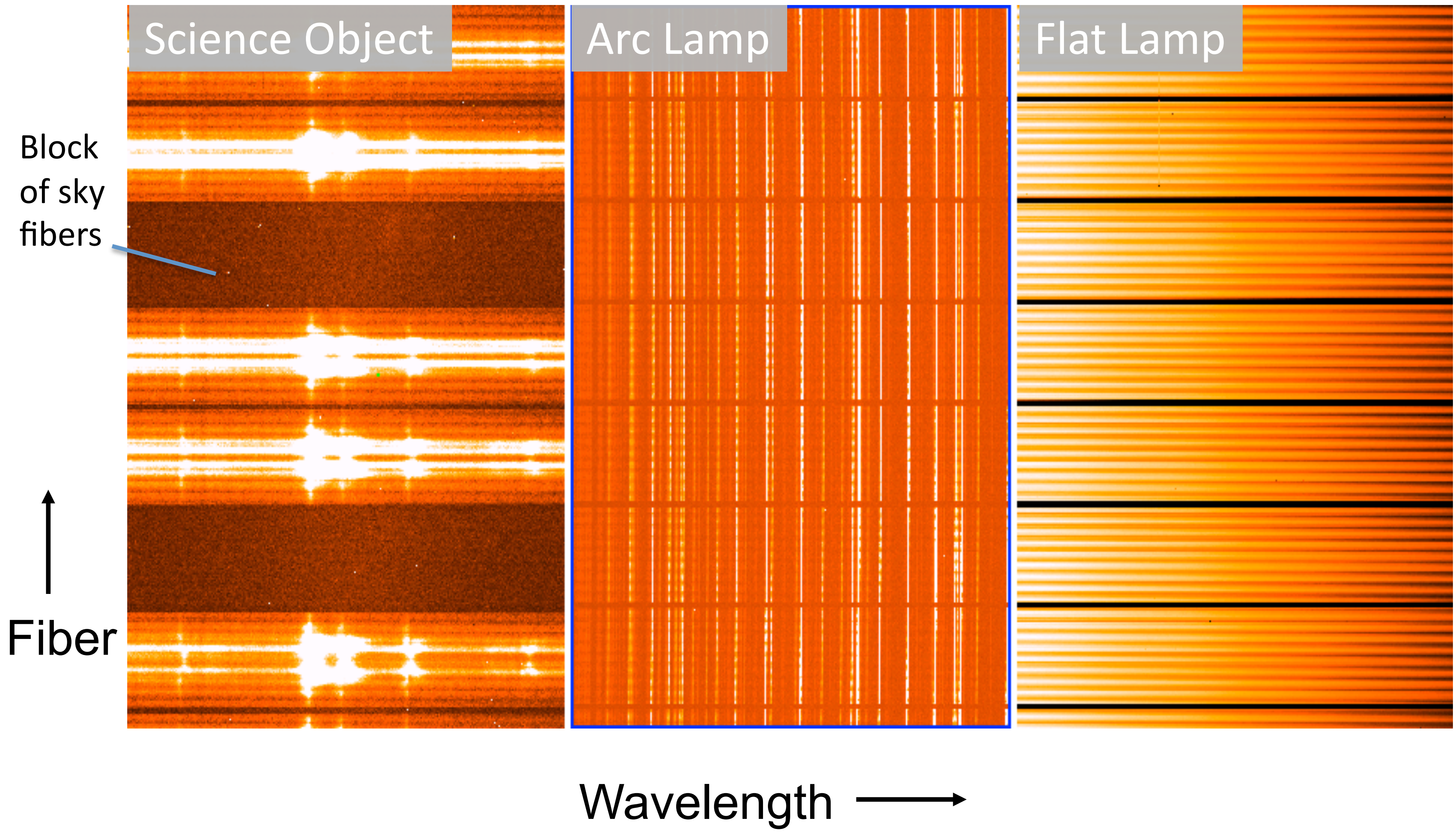


- Mask Definition File (MDF) provides sky coordinates of each fibre on CCD
- Together with wavelength calibration, provide translation from CCD (x,y) to data-cube (RA,Dec,λ)

Typical GMOS Observations

- Science observation
  - Acquisition
    - Field image -> initial offsets
    - Undispersed IFU images -> fine centering
  - Observation sequence:
    - Flat (fringing is flexure-dependent)
    - Sequence of exposures up to 1 hr
    - Flat
- Flux standard star (baseline – not coincident)
- Twilight sky flat
- Daytime calibrations:
  - Arcs
  - Darks (optional)

Typical Raw GMOS Data



GMOS IFU Reduction

- Basic IRAF script on the web
- Forms the basis of this tutorial
- Good starting point for basic reduction
- Aim is to get to a combined data cube with basic calibration (wavelength, transmission…)
- Dataset:
  - SV data on NGC1068 from 2001
  - 2-slit mode IFU -> 5”x7” FoV per pointing
  - 2x2 mosaic for field coverage
  - B600 grating, targeting H-alpha and co.
  - Bias is prepared already
  - Twilight sky included
  - Flux standard also included – not described here

Arranging your files - suggestion

Calibs/ - All baseline daytime calibrations

└ YYYYMMDD/ - daycals from different dates

Science/ - All science data

└ Obj1/ - First science object

  └ YYYYMMDD/ - First obs date (if split over >1 nights)

    └ Config/ - e.g. 'R400' (if using multiple configs)

  └ Merged/ - Merged science and subsequent analysis

Stars/ - All velocity/flux standards – subdir as per science

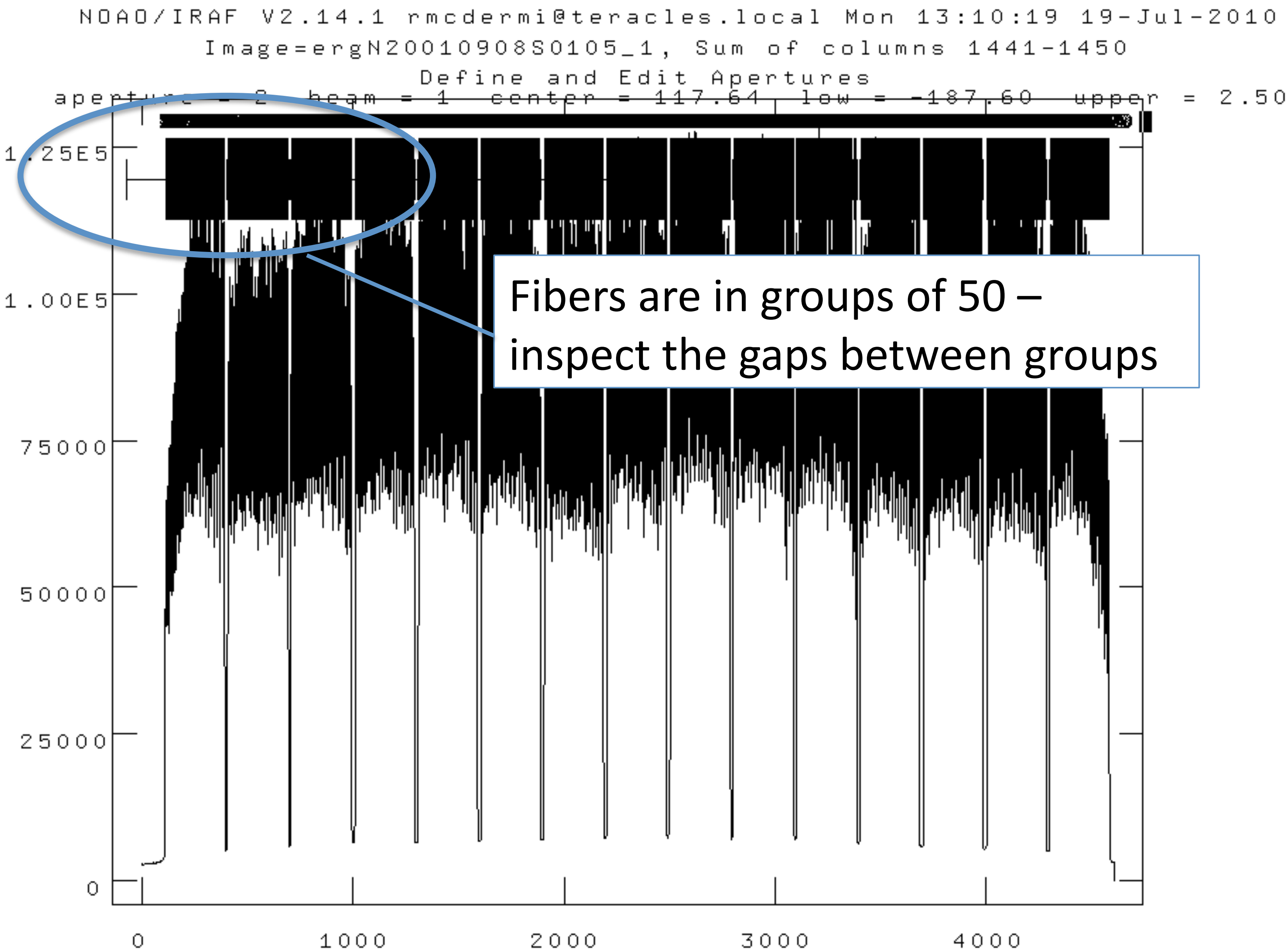
Scripts/

Step 1: Where are the spectra?

- Crucial step is to make sure the spectra can be traced on the detector
- Use the flat lamp to find the fibers on the detector, and trace them with wavelength

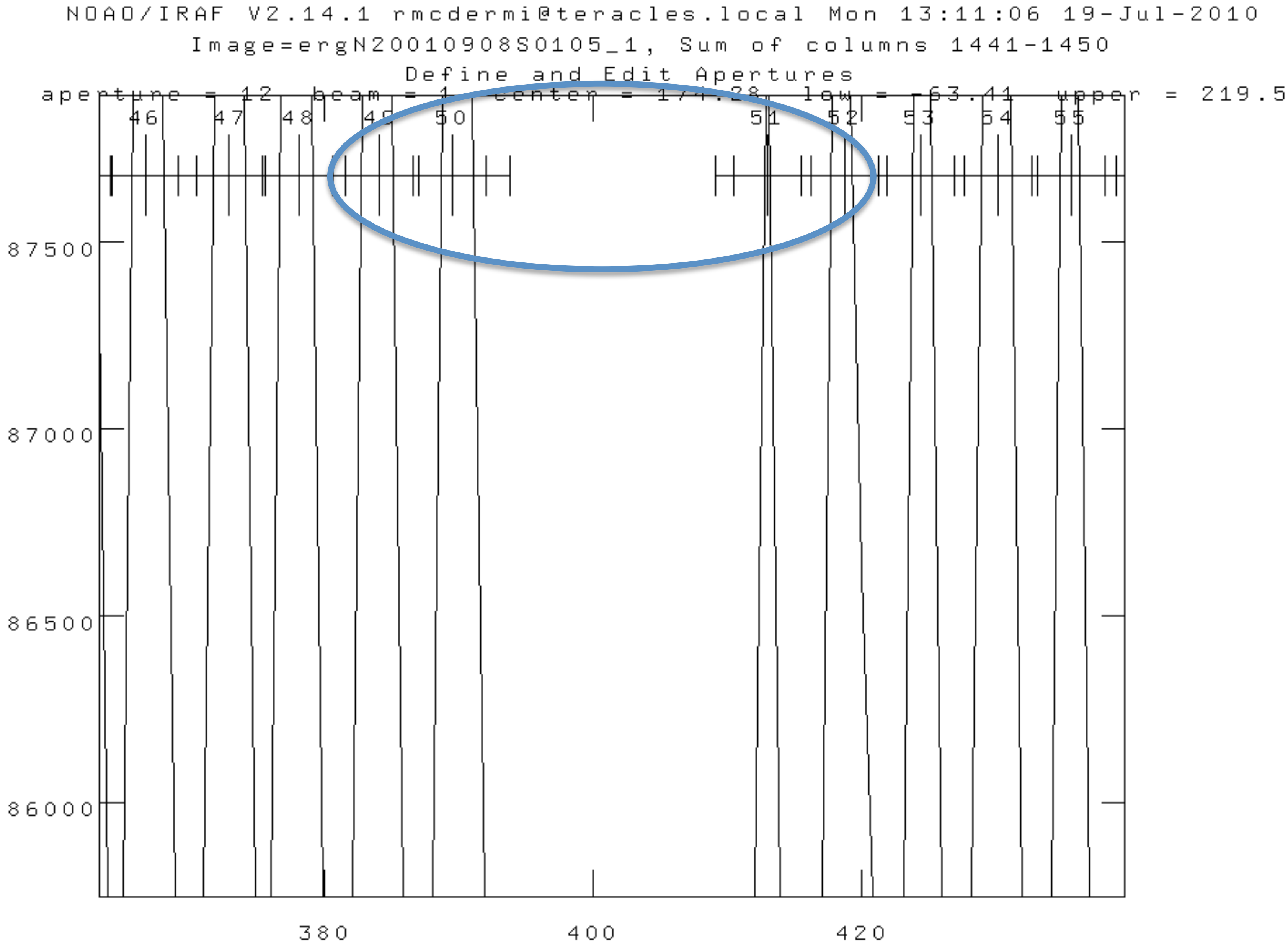
```
gfreduce N20010908S0105 fl_gscrrej- fl_wavtran- fl_skysub-
 fl_inter+ fl_over+ slits=both
```

Step 1: Where are the spectra?



Fibers are in groups of 50 – inspect the gaps between groups

Step 1: Where are the spectra?



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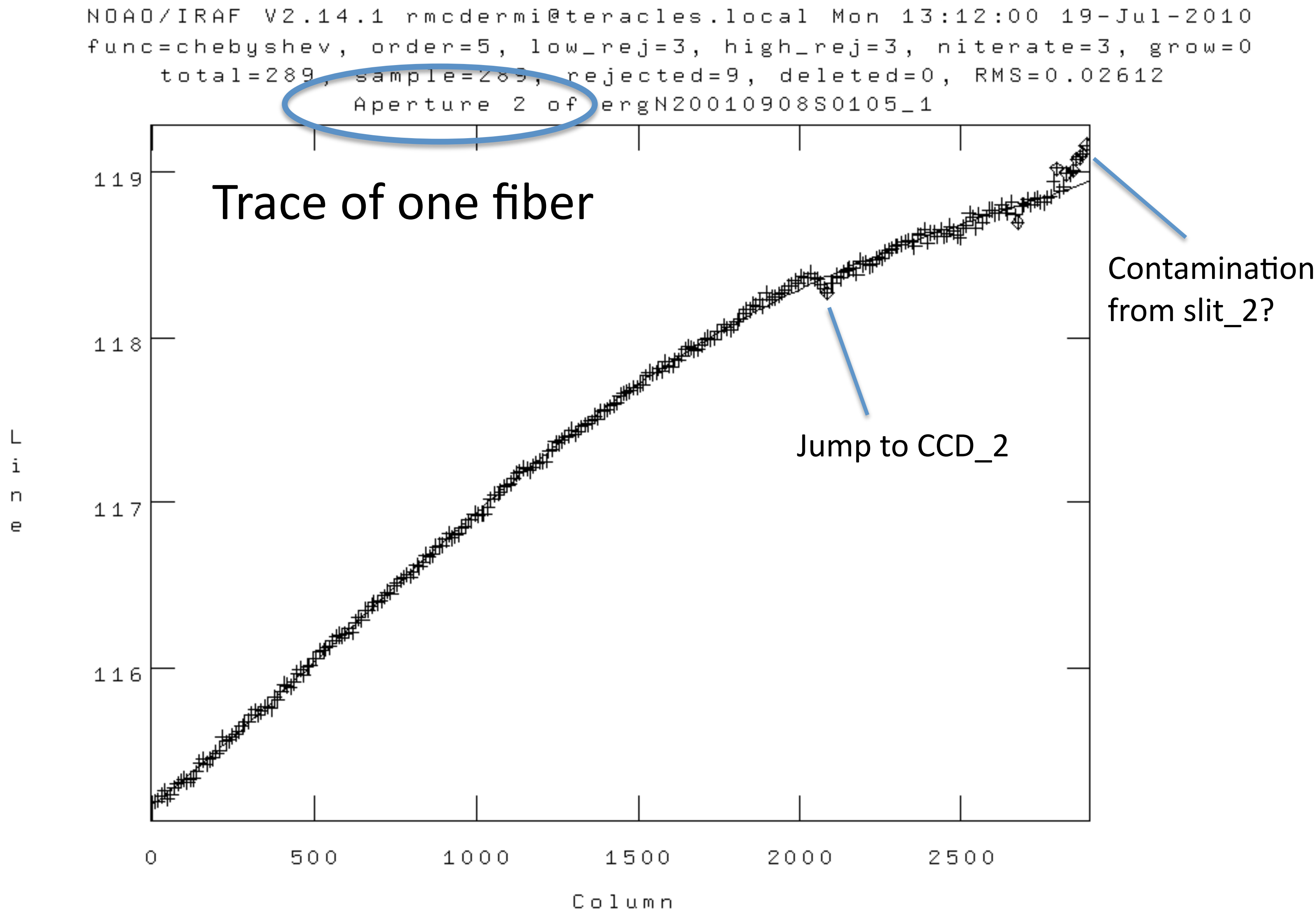

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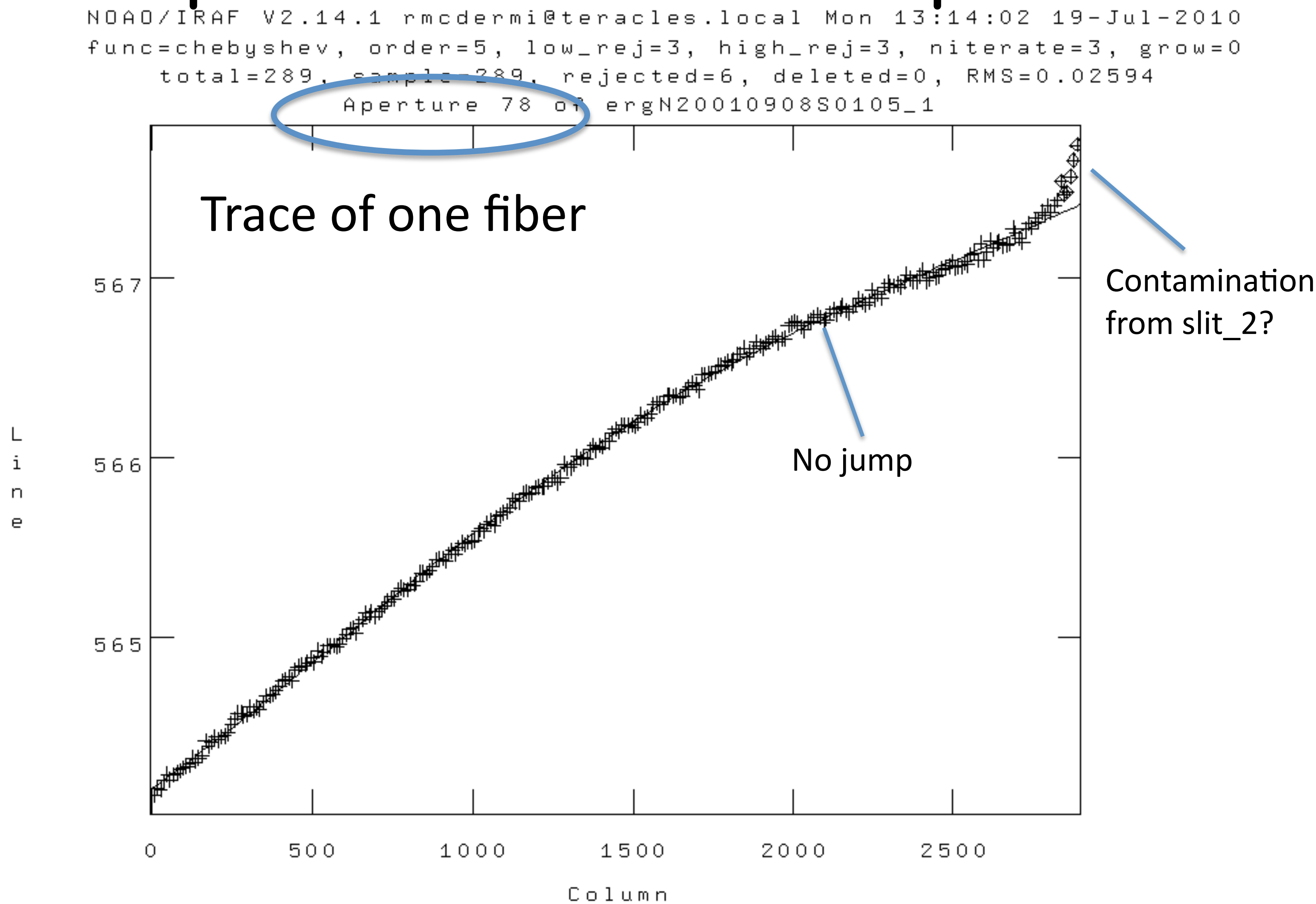

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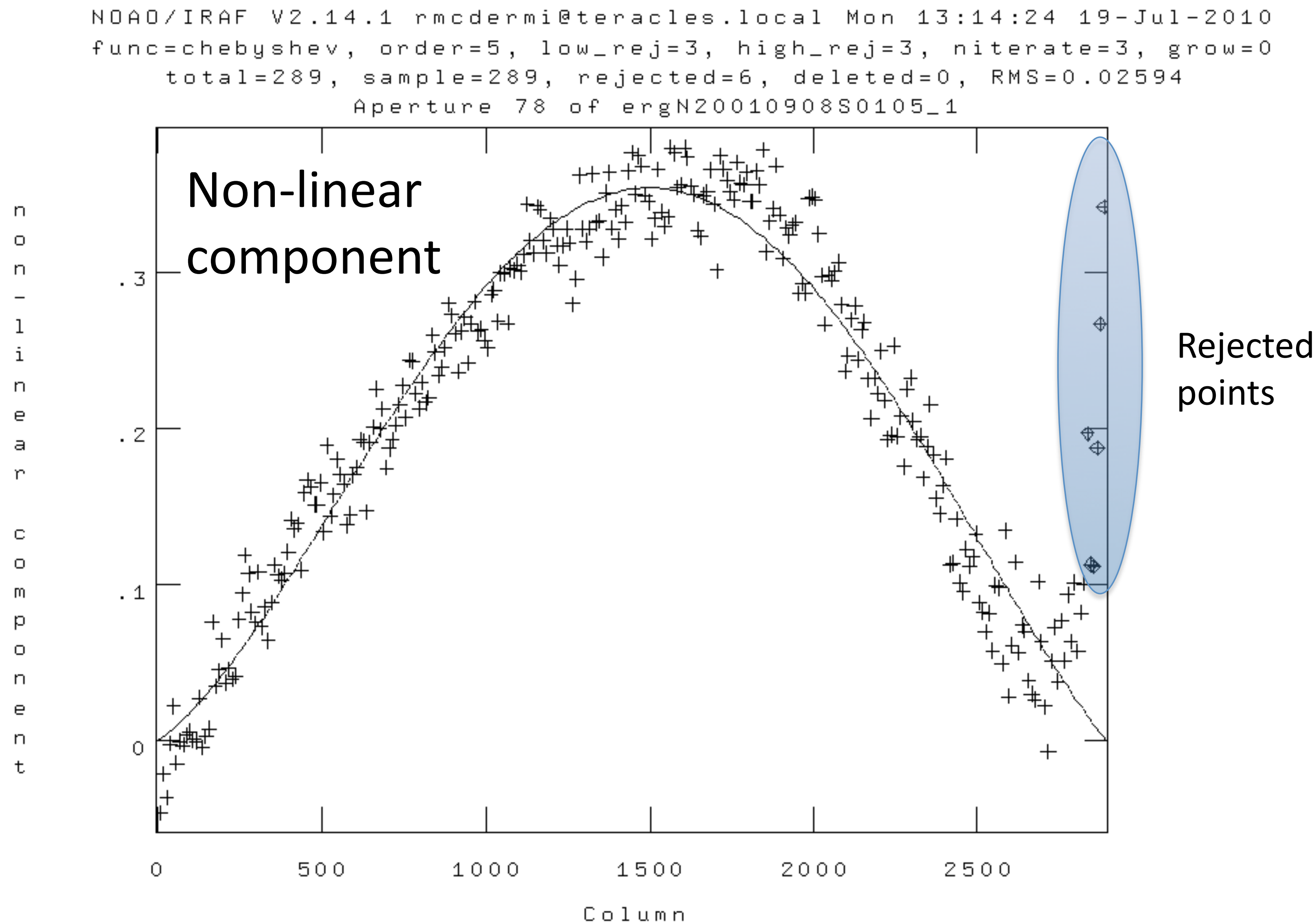

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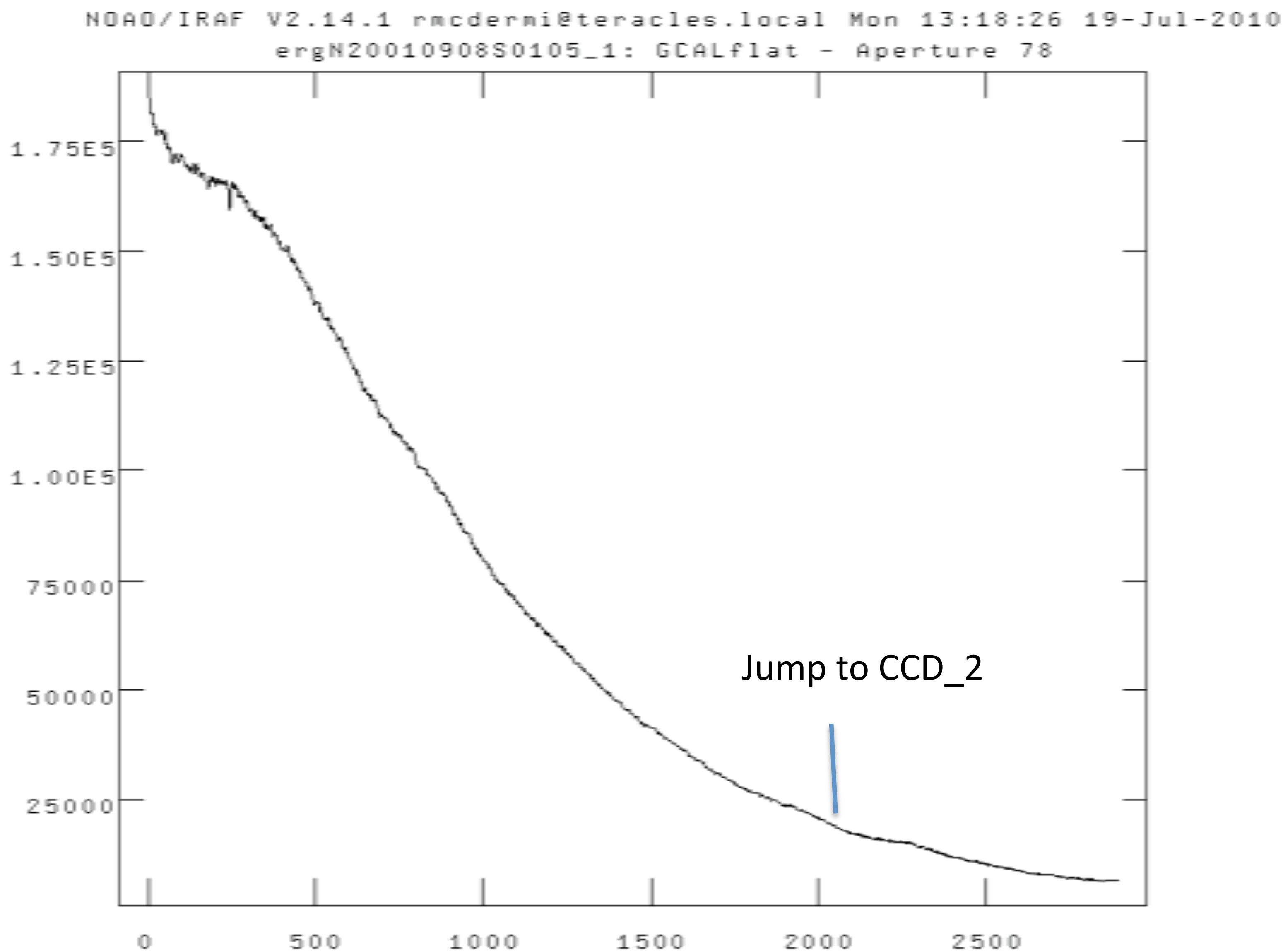
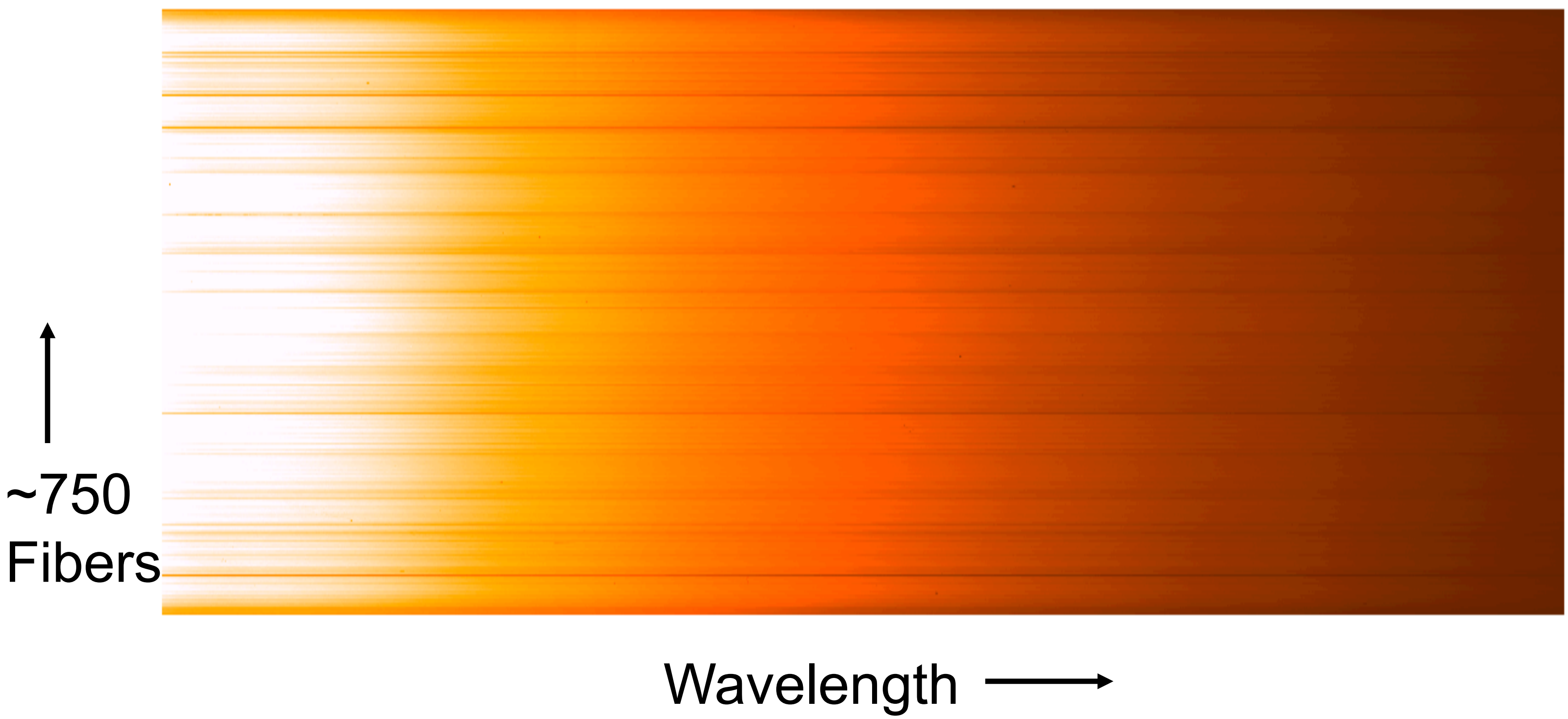


Step 1: Where are the spectra?

- Following extraction, data are stored as 2D images in one MEF (one image per slit)
- This format is VERY useful for inspecting the datacube



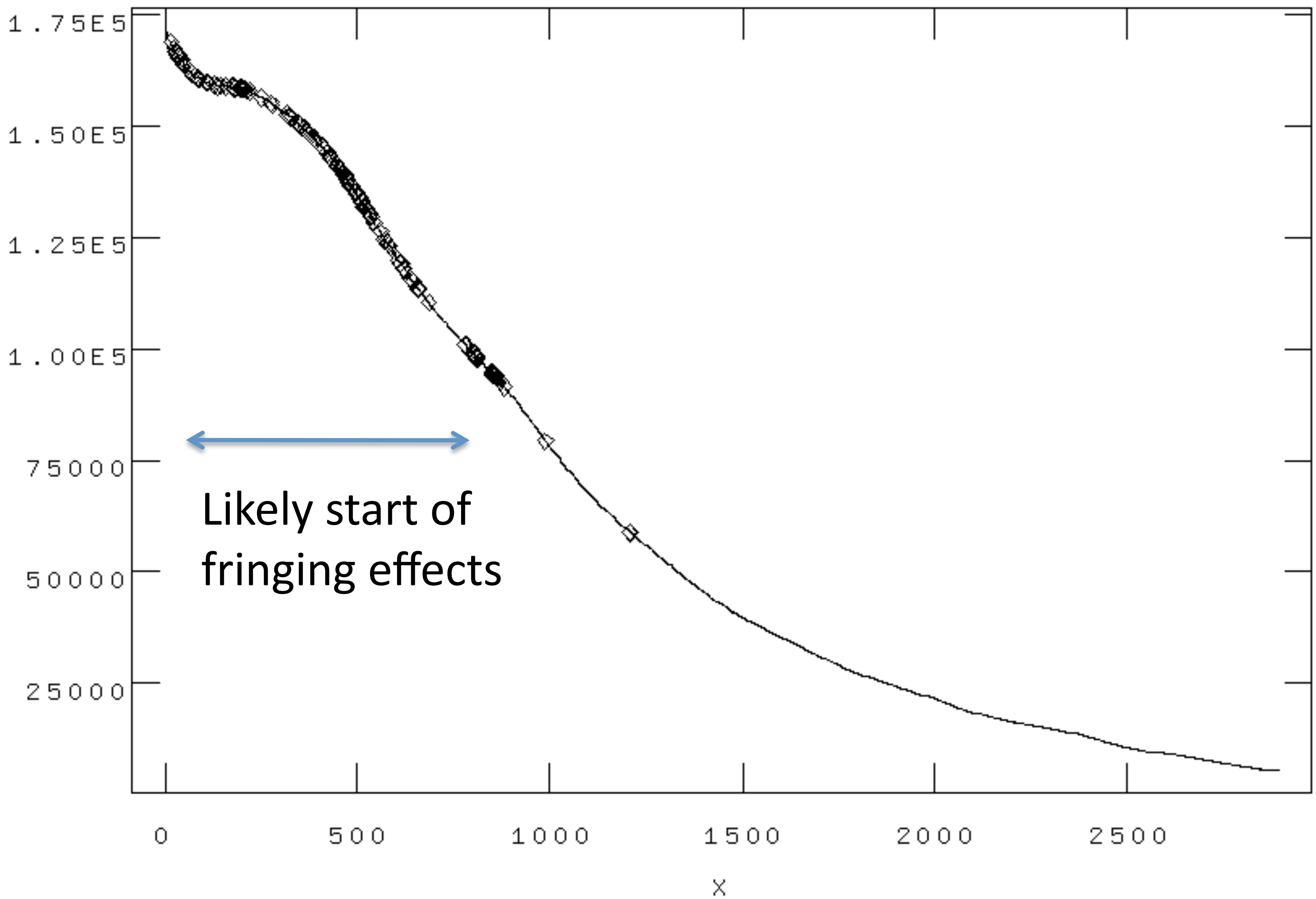
Step 2: Prepare the flat-field

- Flat-fielding has two components:
  - Spectral FF:
    - correct for instrument spectral transmission and pixel response
    - Use black body lamp and divide by fitted smooth function
  - Spatial FF:
    - correct for the illumination function & fiber response
    - Use twilight sky exposure to renormalize the (fit-removed) flat lamp

```
gfresponse ergN20010908S0105 ergN20010908S0105_resp112
   sky=ergN20010908S0112 order=95 fl_inter+ func=spline3
   sample="*”
```

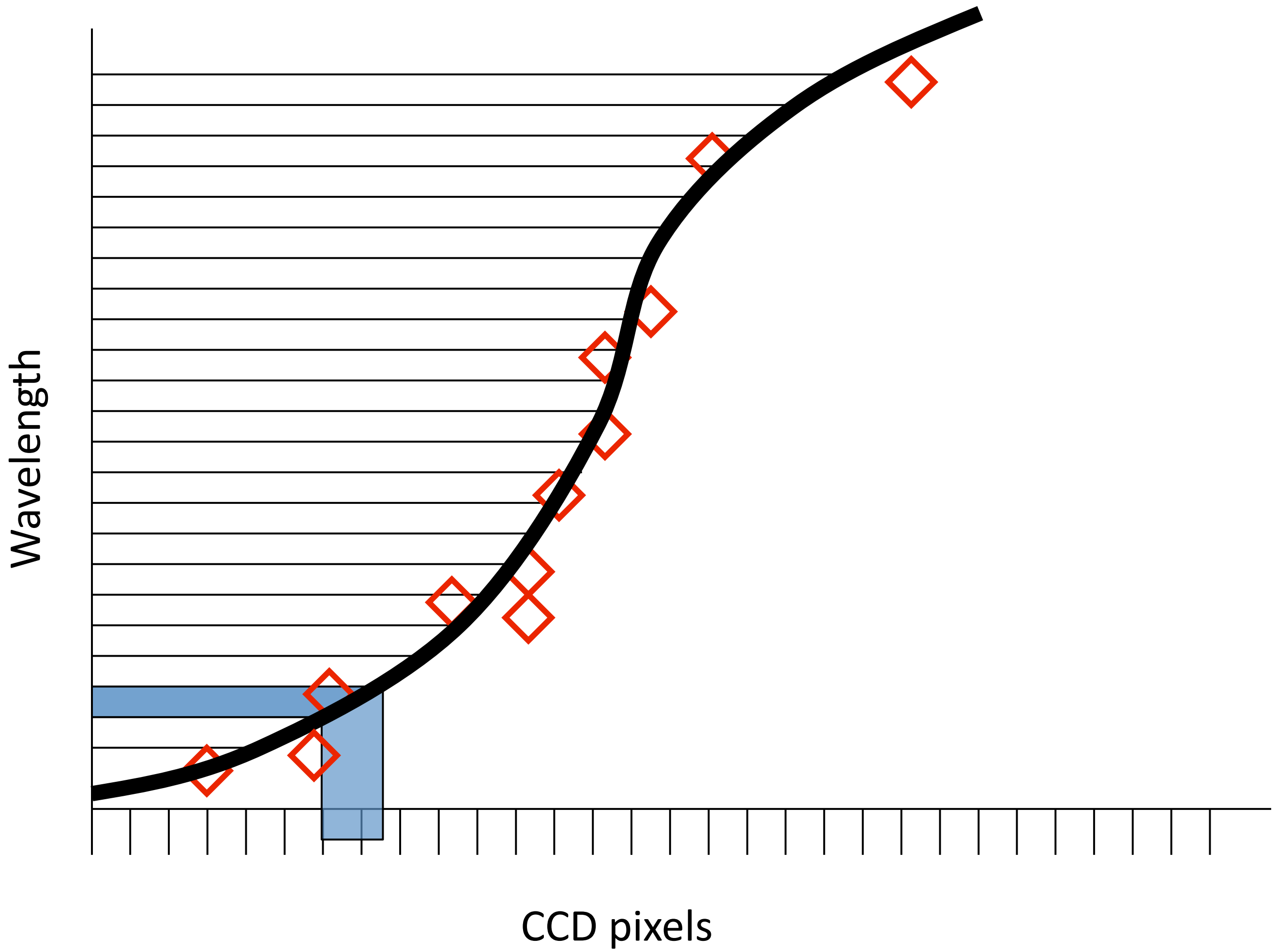
Step 2: Prepare the flat-field

- Fit to the flat lamp



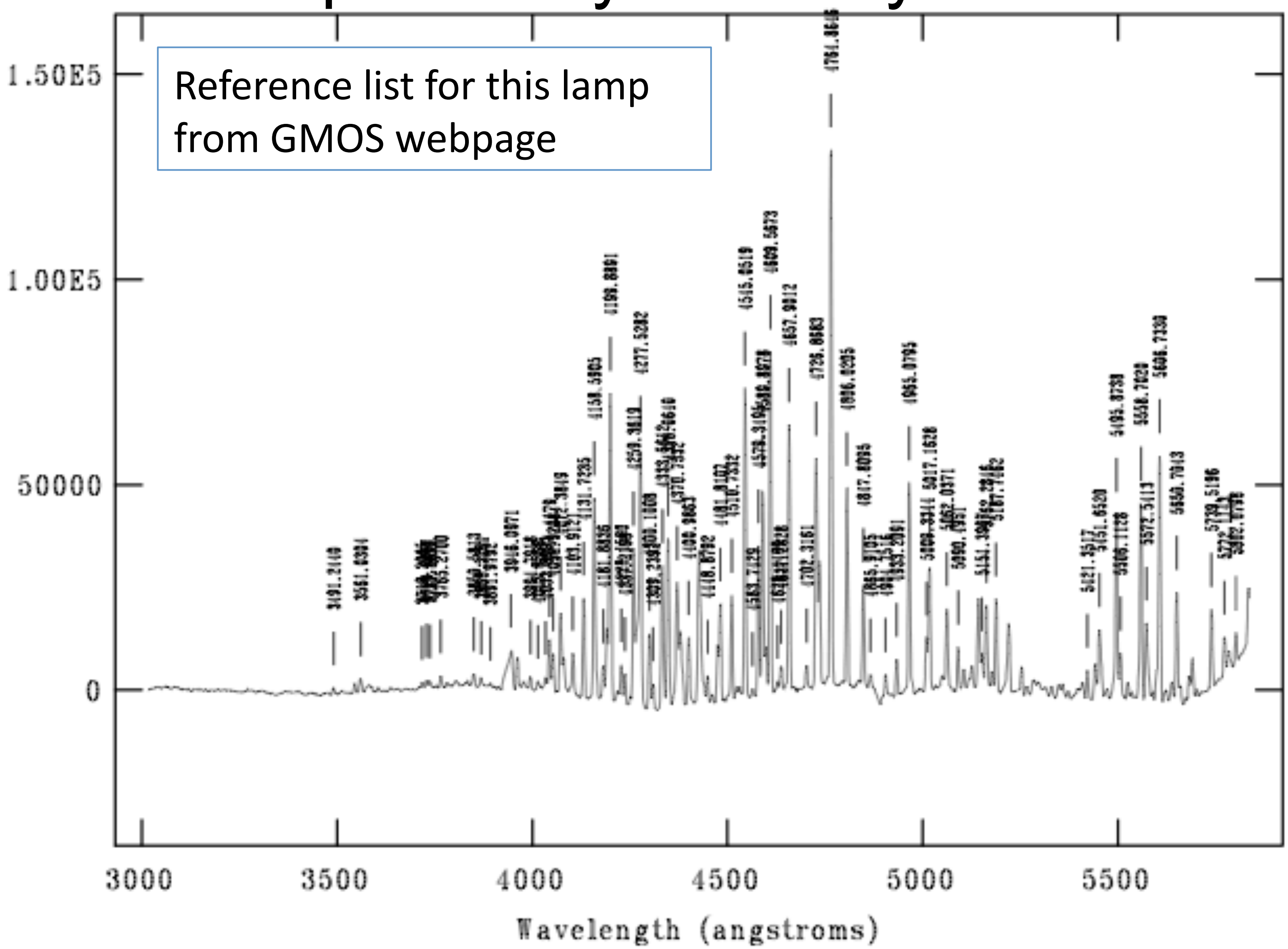
Step 3: Wavelength Calibration

- How can we re-sample the data to have linear wavelength axis?
$\Rightarrow$ Find dispersion function: relationship between your pixels and absolute wavelength



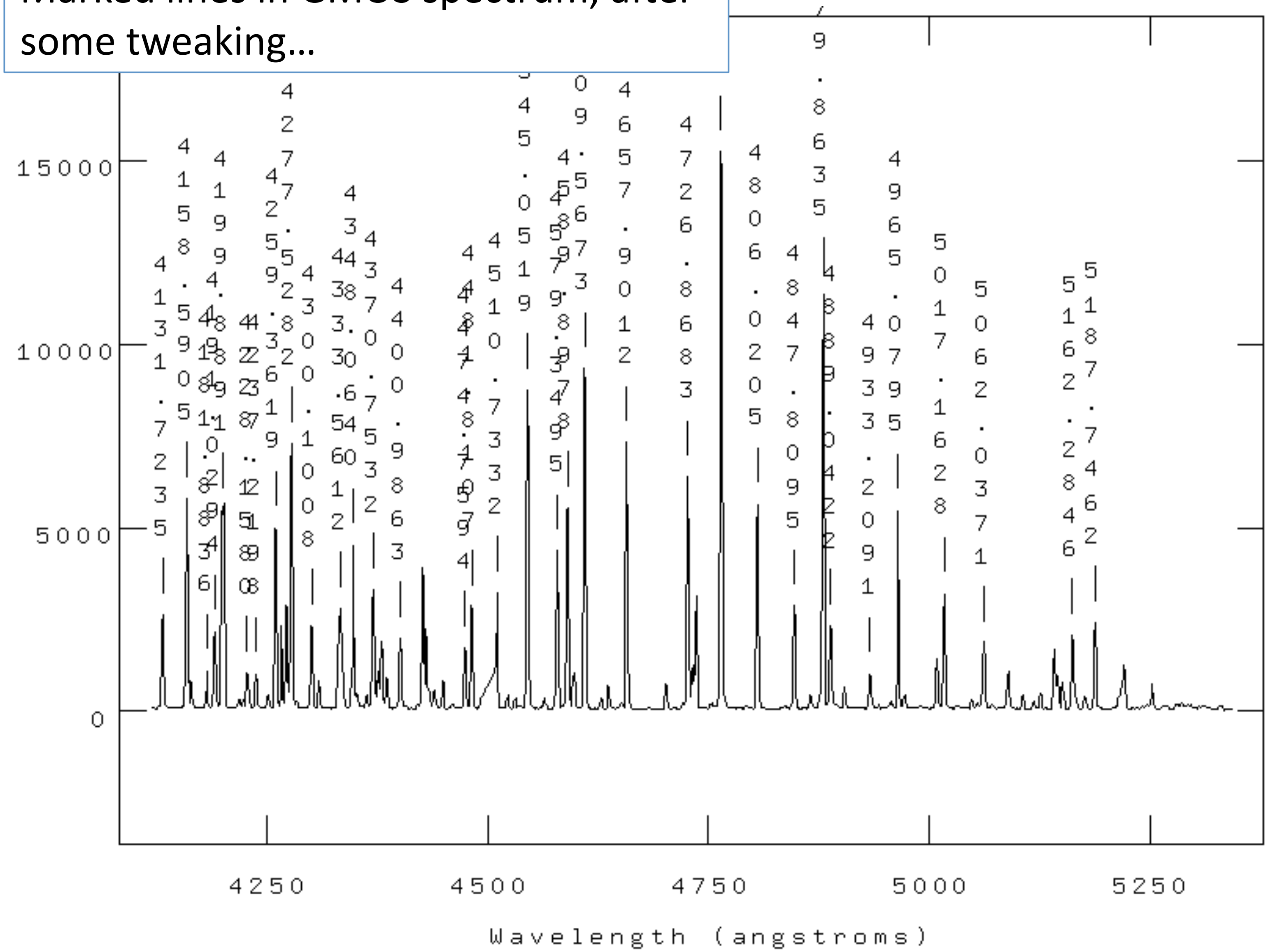
Step 3: Wavelength Calibration

- First step: Identify lines in your arc frame



Step 3: Wavelength Calibration

Marked lines in GMOS spectrum, after some tweaking…



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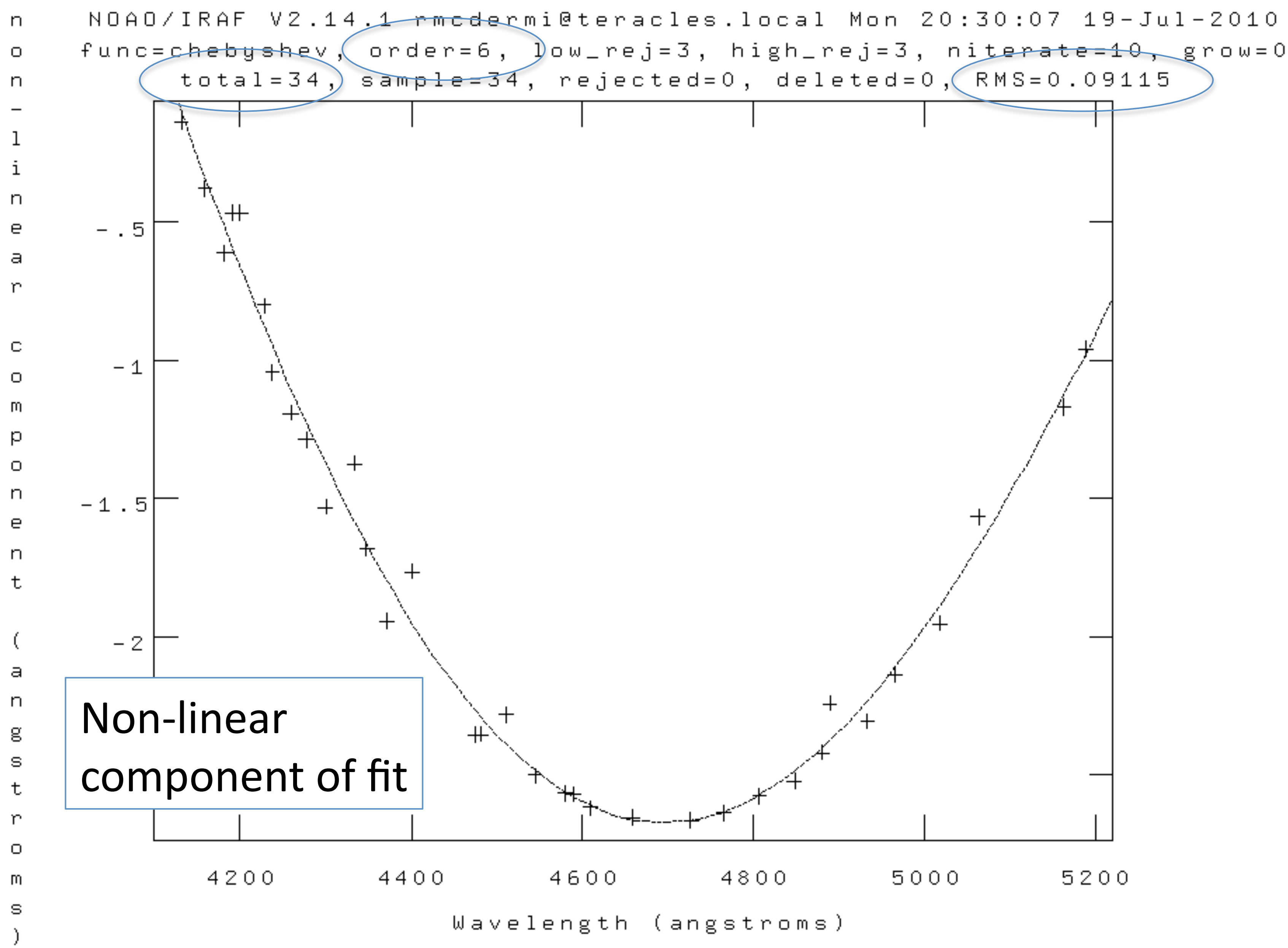


Step 3: Wavelength Calibration

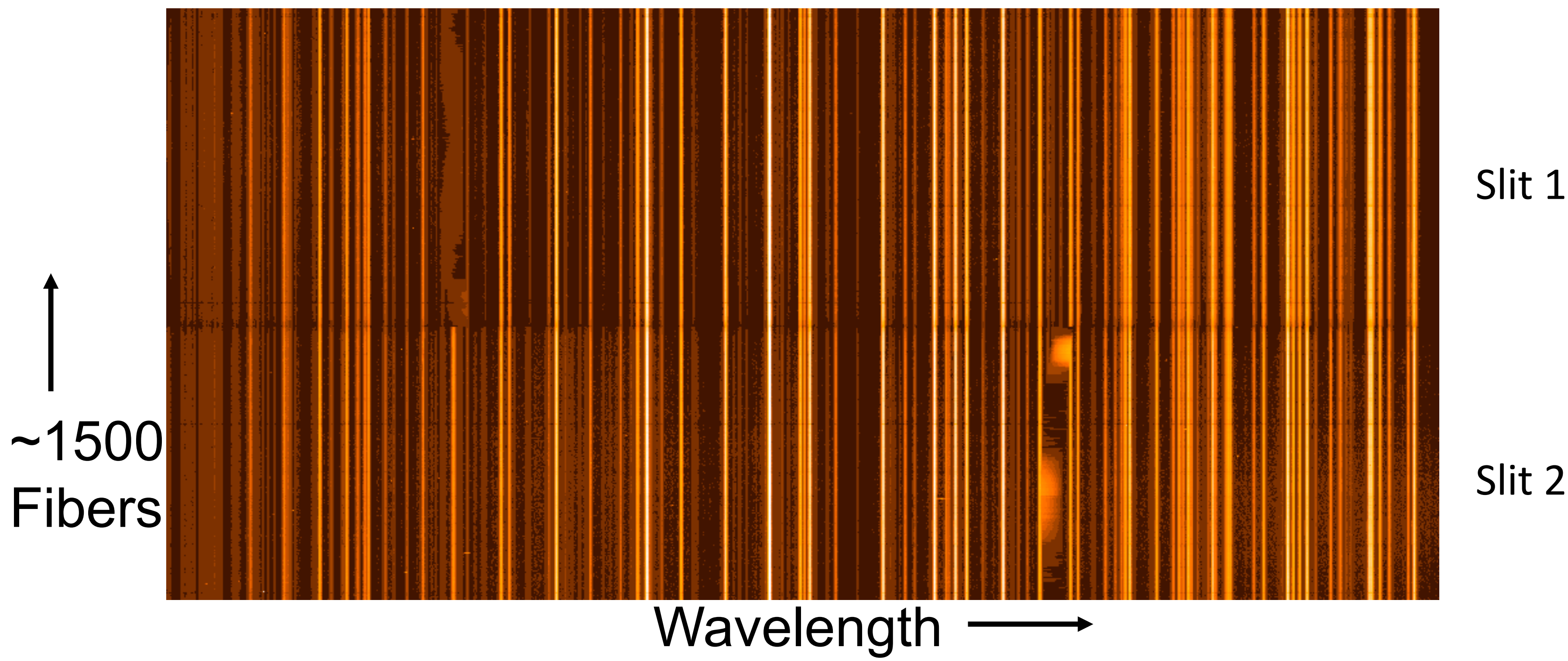
```
xterm
 Reference image = ergN20010908S0108_001, New image = ergN20010908S0108_001, Refit = yes
          Image Data      Found     Fit Pix Shift  User Shift  Z Shift     RMS
ergN20010908S0108_001 - Ap 375 34/34   45/46    -0.0492      0.0231  4.22E-6    0.136
Fit dispersion function interactively? (no|yes|NO|YES) (no): no
ergN20010908S0108_001 - Ap 374 46/46   46/46     0.0369     -0.0172  -3.1E-6    0.134
Fit dispersion function interactively? (no|yes|NO|YES) (no): no
ergN20010908S0108_001 - Ap 373 46/46   46/46    -0.0211     0.00978  2.02E-6     0.13
Fit dispersion function interactively? (no|yes|NO|YES) (no): no
ergN20010908S0108_001 - Ap 372 46/46   46/46     0.0425     -0.0196  -4.2E-6    0.125
Fit dispersion function interactively? (no|yes|NO|YES) (no): no
ergN20010908S0108_001 - Ap 371 46/46   46/46     0.0913     -0.0421  -9.1E-6    0.127
Fit dispersion function interactively? (no|yes|NO|YES) (no): no
ergN20010908S0108_001 - Ap 370 46/46   46/46     -0.141       0.065  1.40E-5    0.129
Fit dispersion function interactively? (no|yes|NO|YES) (no): no
ergN20010908S0108_001 - Ap 369 46/46   46/46    -0.0304       0.014  3.09E-6    0.133
Fit dispersion function interactively? (no|yes|NO|YES) (no): no
ergN20010908S0108_001 - Ap 368 46/46   46/46      0.115      -0.053  -1.2E-5    0.132
Fit dispersion function interactively? (no|yes|NO|YES) (no): no
ergN20010908S0108_001 - Ap 367 46/46   46/46     -0.128      0.0592  1.29E-5    0.136
Fit dispersion function interactively? (no|yes|NO|YES) (no): no
noergN20010908S0108_001 - Ap 366 46/46   46/46     0.0676     -0.0312  -6.8E-6    0.135
Fit dispersion function interactively? (no|yes|NO|YES) (no):
ergN20010908S0108_001 - Ap 365 46/46   46/46    -0.0548      0.0252  5.61E-6    0.127
Fit dispersion function interactively? (no|yes|NO|YES) (no): no
ergN20010908S0108_001 - Ap 364 46/46   46/46      0.222      -0.103  -2.2E-5    0.133
Fit dispersion function interactively? (no|yes|NO|YES) (no): no
ergN20010908S0108_001 - Ap 363 46/46   46/46     -0.151      0.0698  1.52E-5    0.133
Fit dispersion function interactively? (no|yes|NO|YES) (no): no
ergN20010908S0108_001 - Ap 362 46/46   46/46     -0.253       0.117  2.53E-5    0.138
Fit dispersion function interactively? (no|yes|NO|YES) (no): no
ergN20010908S0108_001 - Ap 361 46/46   46/46      0.166     -0.0767  -1.7E-5    0.135
Fit dispersion function interactively? (no|yes|NO|YES) (no): no
ergN20010908S0108_001 - Ap 360 46/46   46/46      0.101     -0.0466  -1.0E-5    0.131
Fit dispersion function interactively? (no|yes|NO|YES) (no): no
ergN20010908S0108_001 - Ap 359 46/46   46/46     -0.244       0.112  2.44E-5    0.127
Fit dispersion function interactively? (no|yes|NO|YES) (no): no
ergN20010908S0108_001 - Ap 358 46/46   46/46      0.161     -0.0742  -1.6E-5    0.133
Fit dispersion function interactively? (no|yes|NO|YES) (no): no
ergN20010908S0108_001 - Ap 357 46/46   46/46    -0.0389       0.018  3.91E-6    0.134
Fit dispersion function interactively? (no|yes|NO|YES) (no): no
ergN20010908S0108_001 - Ap 356 46/46   46/46     0.0983     -0.0453  -9.9E-6    0.135
Fit dispersion function interactively? (no|yes|NO|YES) (no):
ergN20010908S0108_001 - Ap 355 46/46   46/46     -0.114      0.0524  1.15E-5    0.135
Fit dispersion function interactively? (no|yes|NO|YES) (no):
ergN20010908S0108_001 - Ap 354 46/46   46/46     0.0904     -0.0417  -9.1E-6    0.132
Fit dispersion function interactively? (no|yes|NO|YES) (no):
ergN20010908S0108_001 - Ap 353 46/46   46/46     -0.154       0.071  1.56E-5    0.138
Fit dispersion function interactively? (no|yes|NO|YES) (no):
ergN20010908S0108_001 - Ap 352 46/46   46/46     -0.106      0.0489  1.05E-5    0.131
Fit dispersion function interactively? (no|yes|NO|YES) (no):
ergN20010908S0108_001 - Ap 351 46/46   46/46    -0.0575      0.0265  5.84E-6    0.133
Fit dispersion function interactively? (no|yes|NO|YES) (no):
```

RMS ~0.1 pix

- First solution used as starting point for subsequent fibers
- Usually robust, but should be checked carefully
- Often best to edit the reference line list for added robustness
- Two slits are treated separately – need to repeat

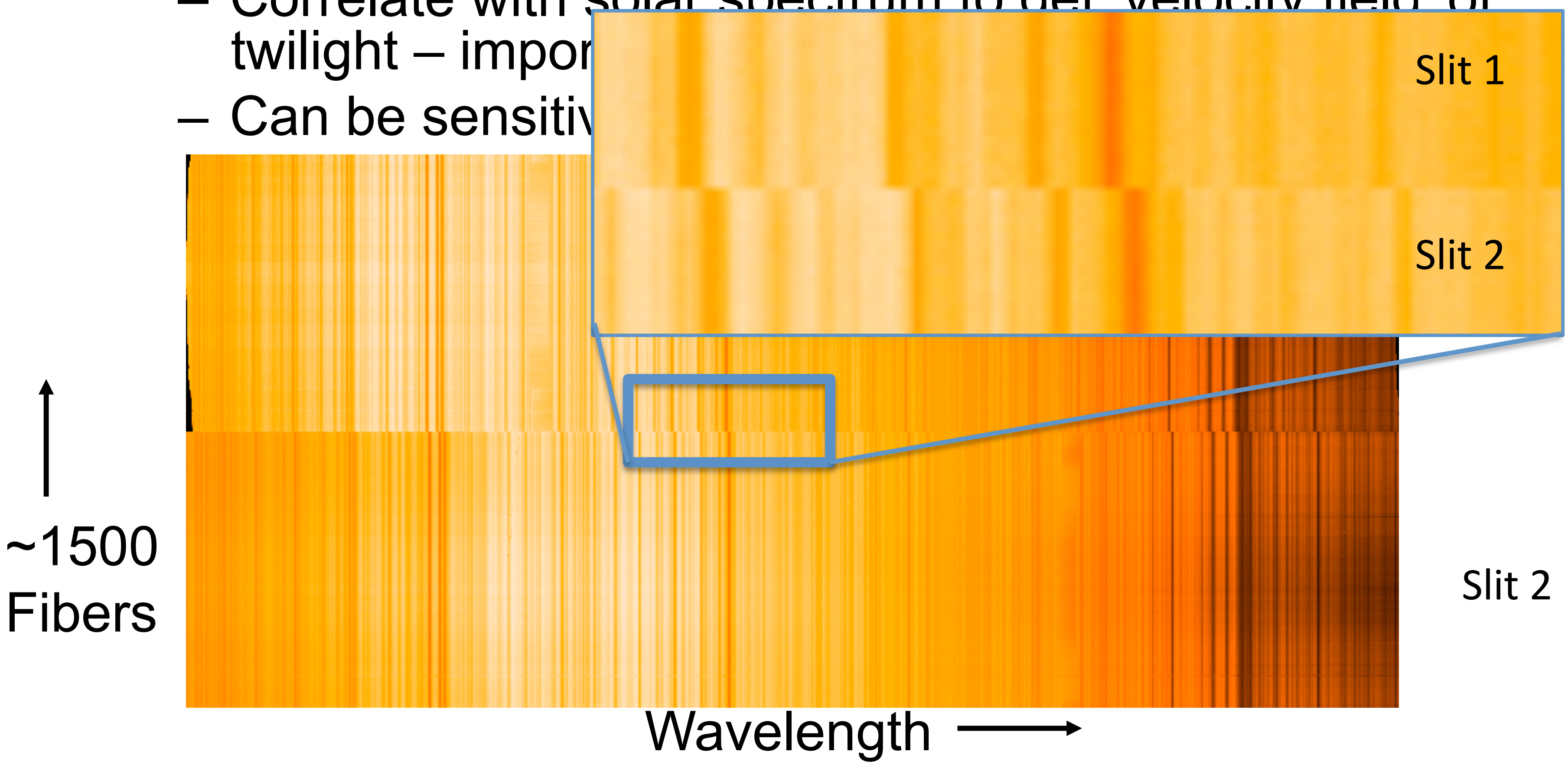
Checking the wavecal

- Testing quality of wavelength calibration is critical
- Not always obvious from your science data
  - May not have skylines
  - How to spot systematic nonlinearities?
- Basic check is to apply calibration to the arc itself, and inspect the 2D image for alignment

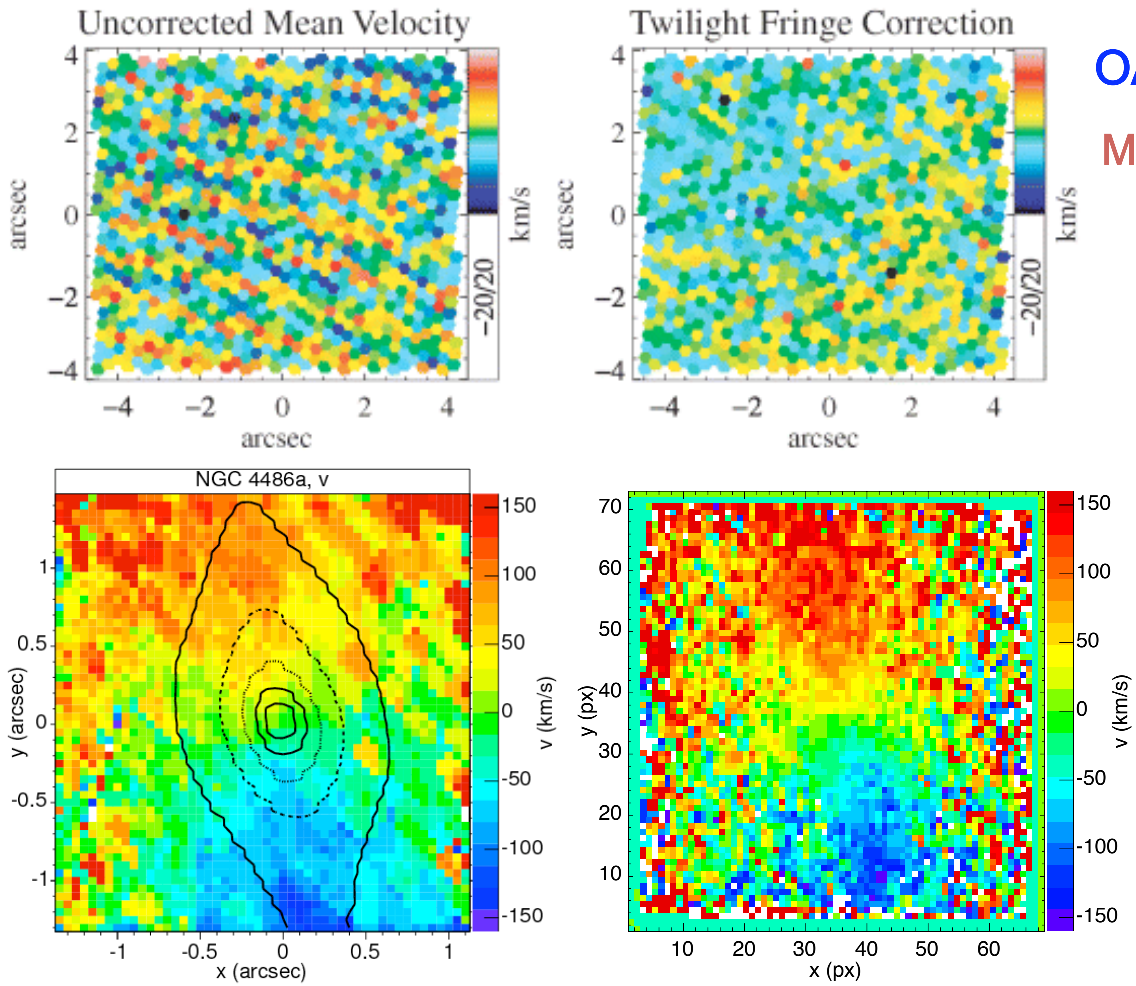


Checking the wavecal

- Twilight sky is also an excellent end-to-end test
  - Reduce it like your science data
  - Check alignment of absorption features
  - Can also compare with solar spectrum
  - Correlate with solar spectrum to get ‘velocity field’ of twilight – impor
  - Can be sensitiv



‘Fringing’ from bad flat fielding



OASIS

McDermid et al. 2006

SINFONI data on NGC 4486a

Nowak et al.

Such effects would be completely missed in long-slit data….

Step 4: Reduce science data!

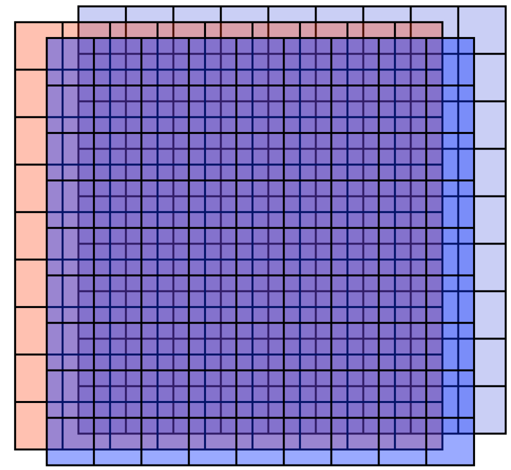
- You have now the following:
  - Bias
  - Spectral trace
  - Flat-field
  - Wavelength solution
- Now run gfreduce to:
  - Bias-subtract
  - Extract traces
  - Apply flat-fielding
  - Reject cosmic rays (via Laplacian filter)
  - Apply wavelength solution

```
gfreduce N20010908S0101 fl_inter- verb+ refer=ergN20010908S0105
   recenter- trace- fl_wavtran+ wavtran=ergN20010908S0108
   response=ergN20010908S0105_resp112 fl_over+ biasrows="3:64”
   slits=both fl_gscrrej+
```

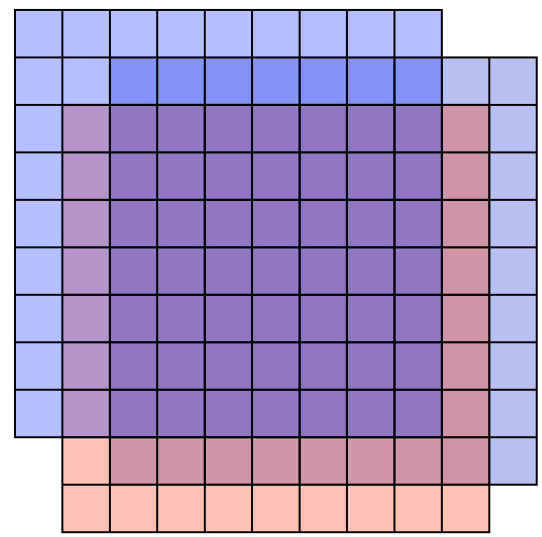
Co-Adding Data Cubes

Two approaches:

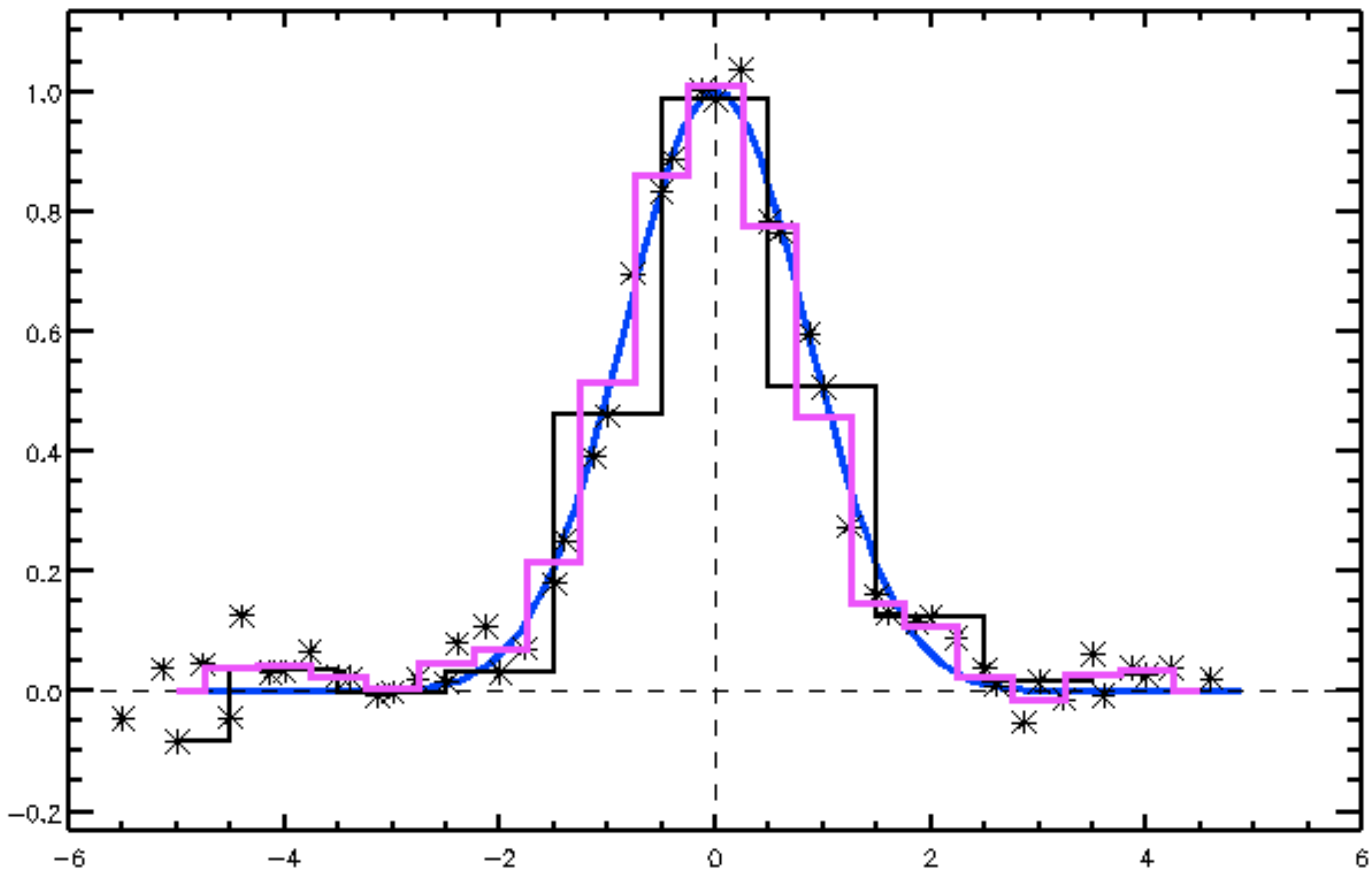
1. Dithering by non-integer number of spaxels:
    - Allows over-sampling, via 'drizzling'
    - Resampling introduces correlated noise
    - Good for fairly bright sources



2. Dither by integer number of spaxels
    - Allows direct 'shift and add' approach
    - No resampling:- better error characterisation
    - Assumes accurate (sub-pixel) offsetting
    - Suitable for 'deep-field' applications



Over-sampling



The deep field approach

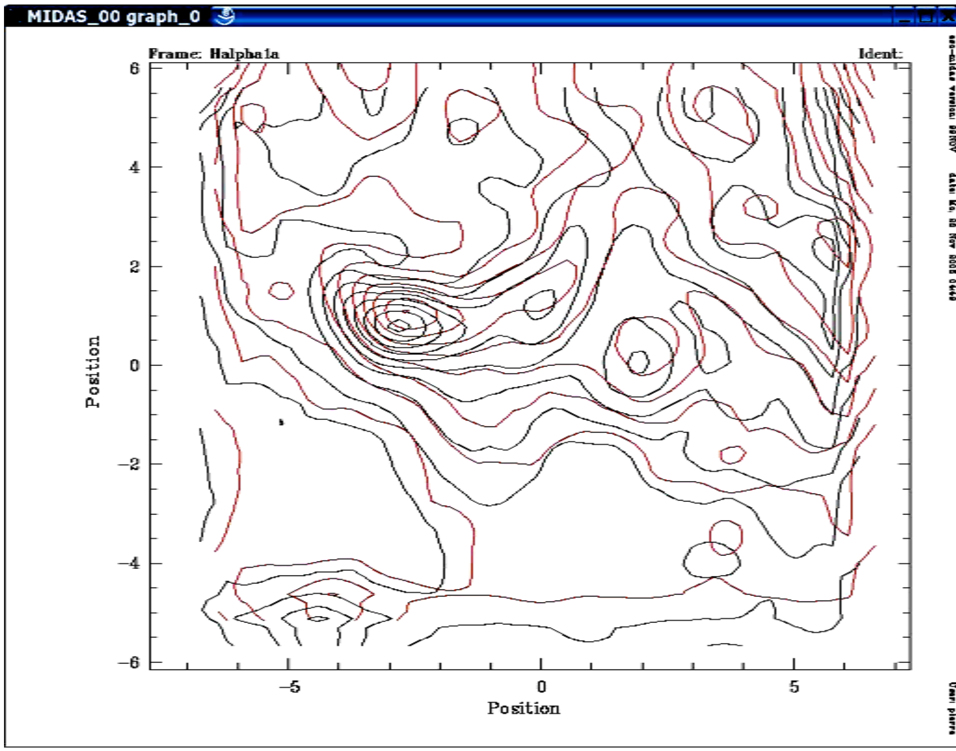
- Multiple exposures of a single field of view
- Aiming at pushing the detection limits of an instrument
- Systematic dithering of the exposures
  - Allows to easily spot and eliminate artefacts
  - Reduces the flat-field errors
  - Noise is uncorrelated (as far as possible)
- Strategy for data cubes identical to the one for images

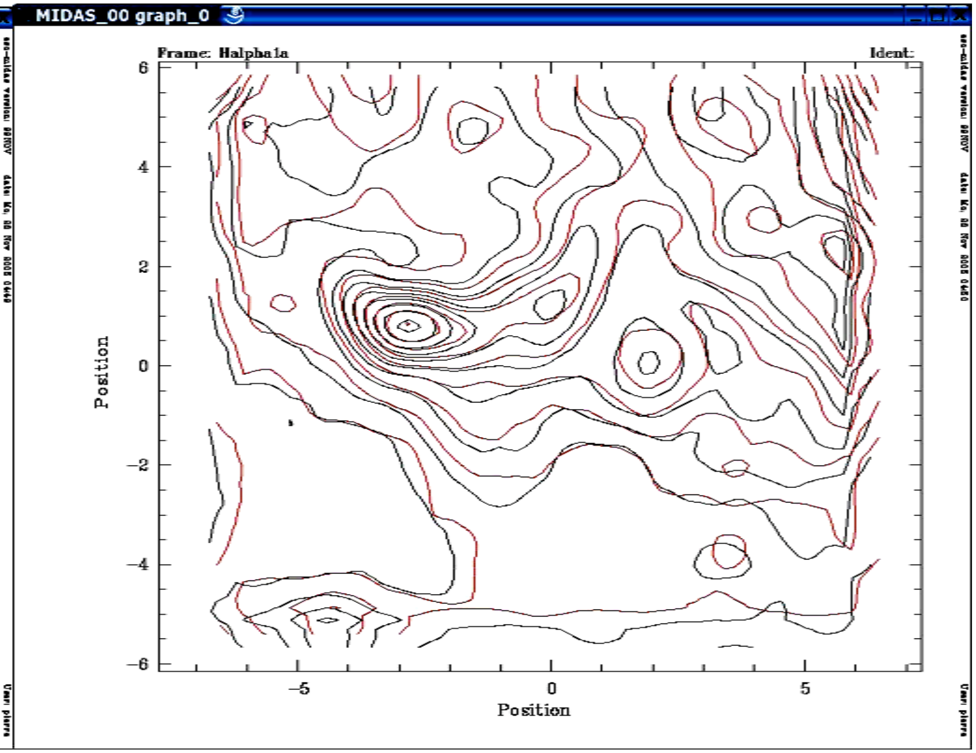
Determine the relative positioning

- Trust the telescope pointing / header information:
  - Often have sub-arcsecond sampling and you want sub-spaxel accuracies…
  - Telescope pointing accuracy maybe not good enough
  - For ‘invisible’ sources, likely the only way to co-add
  - Positioning uncertainty will degrade the PSF

- Obtain the information from the data:
  - Use a “sharp” morphological feature (e.g. the nucleus of a galaxy, a star…) if available
  - Using centroids or spatial Gaussian profile fitting to get the position of the punctual reference source
  - Use contour plots of a reconstructed image to get the relative positioning between two data cubes

Determine the relative positioning





- Difficulties:
  - Fairly subjective method
  - Changes in observing conditions mess up things!
  - Noise in the individual exposures does not help

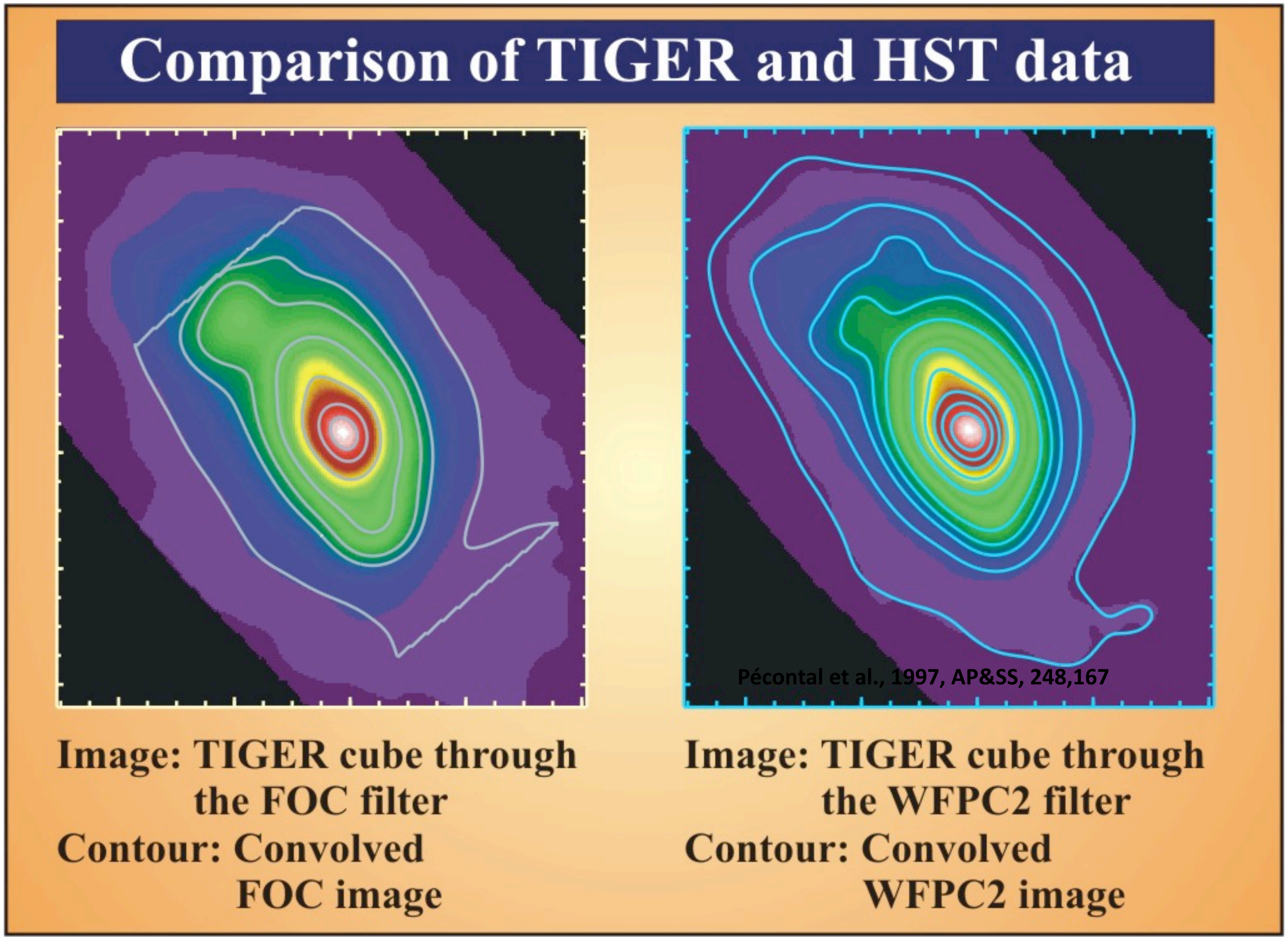
Normalization

- Relative normalization
  - Transparency can change between exposures
  - Need to track these changes and correct for them (the absolute radiometric calibration of the data does not take care about them)

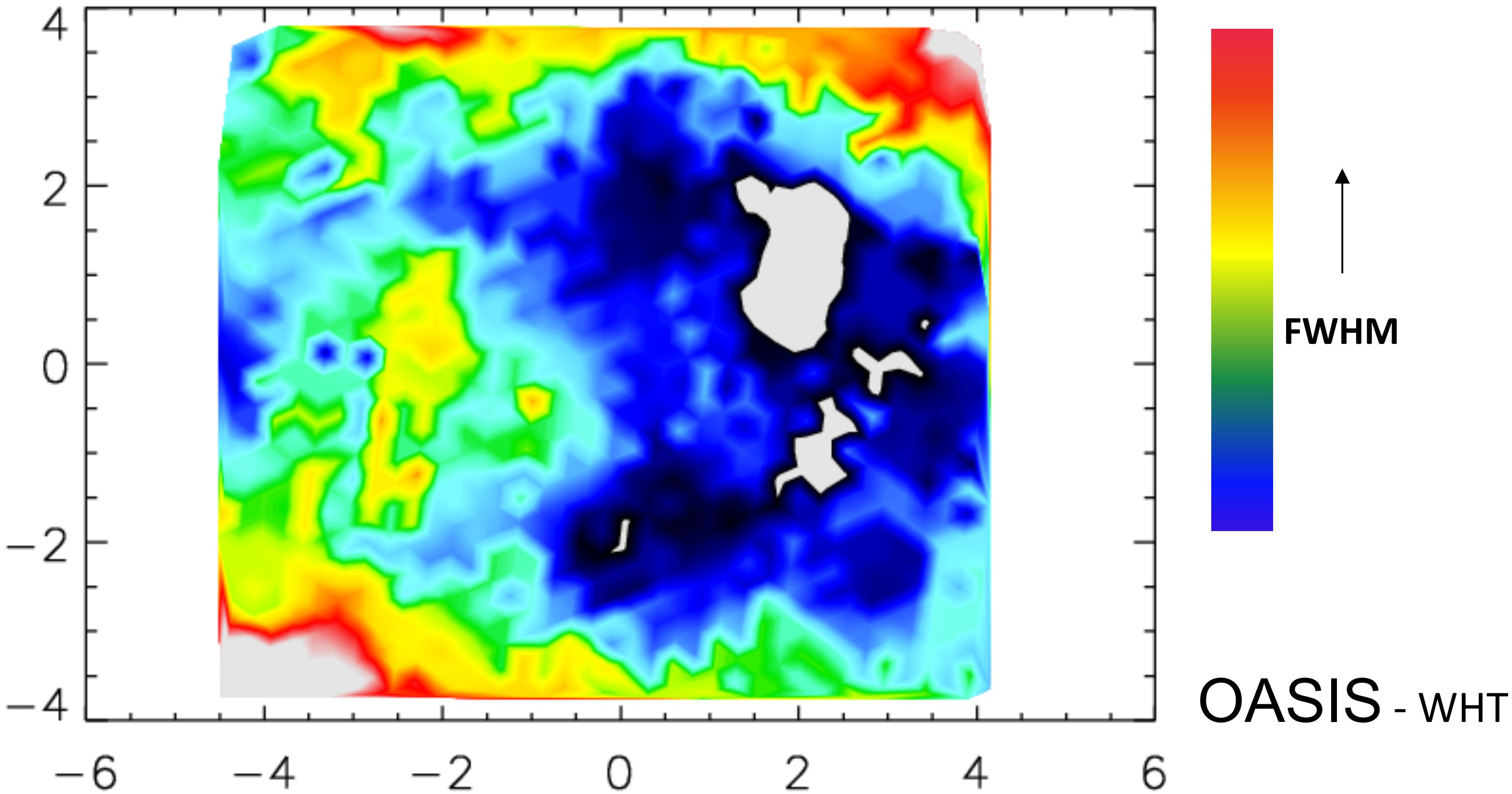
- Absolute normalization of the exposures
  - Best way = to use of spectro-photometric standard stars
  - Cross-check with images from the same field of view
    - Collapse the data cube with weights corresponding to the image filter
    - Compare the data cube with the image

Normalization

Example: kinematics of the ➔ some velocity components are not present in one of the filters but appear in the second one



Spectral Resolution



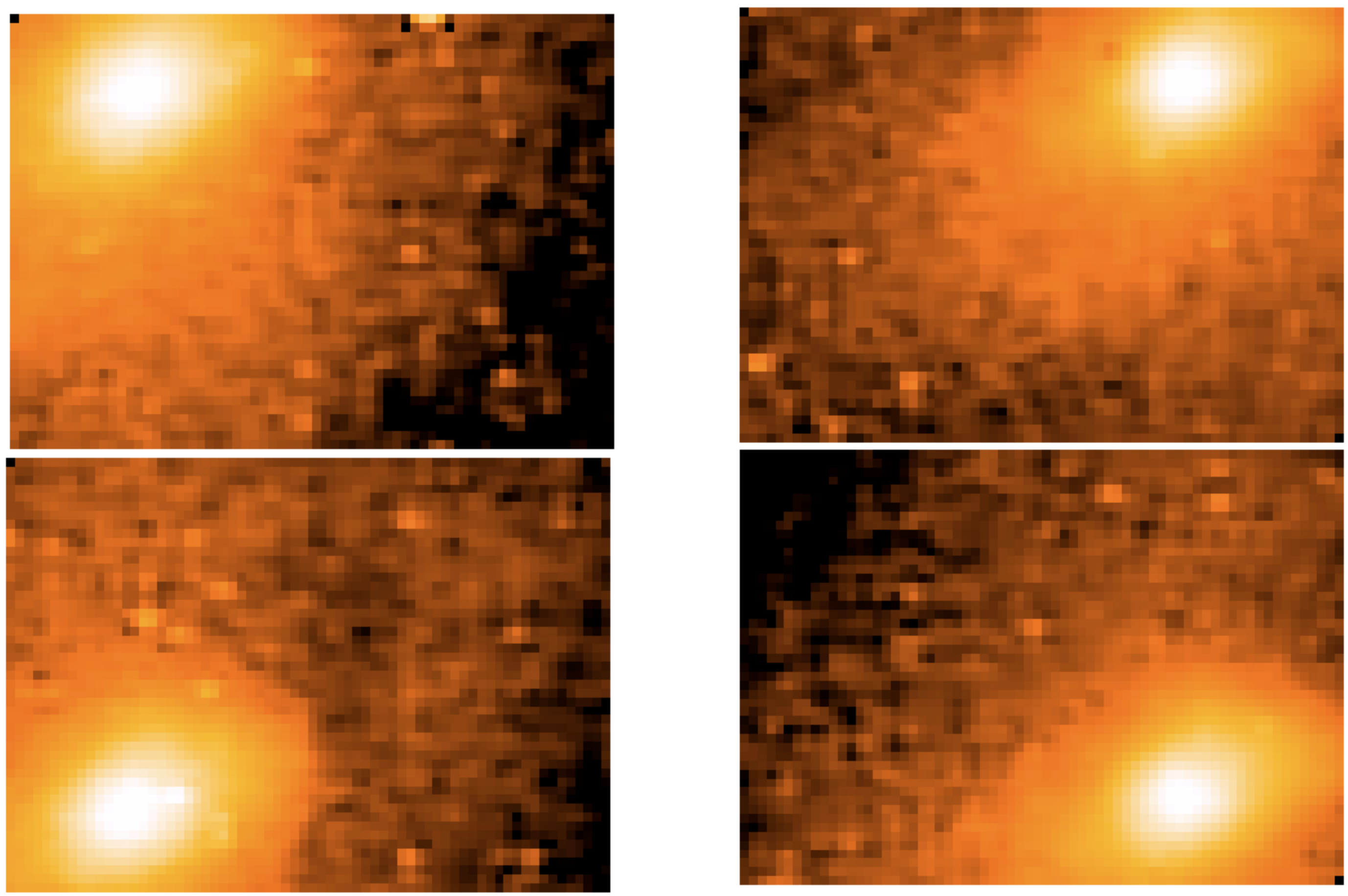
- Variations in spectral PSF across field
- Need to homogenize before merging
- Measured using twilight sky
- Broaden each spectrum: $\sigma^2_{goal} = \sigma^2_{measured} + \sigma^2_{difference}$

Ready to co-add…

- Data cubes are now:
  - Linearized in spatial and spectral domain ✓
  - Share a common spatial coordinate frame ✓
  - Have a uniform spectral resolution across the FoV ✗
  - Have a known common normalization ✗
  - May have relative weights (If very different S/N) ✗
- Just a simple transformation into a common (x,y,l) volume, then combine
  - Ideally this would be a single transformation from the 'raw' data to the new frame, applying the wavelength calibration and spatial distortion correction at the same time
  - More commonly, multiple transformations are used
  - Method here is not optimal, but starting point

Merge Data Cubes

- Create 3D cubes and inspect image planes via ds9
- Measure pixel position of reference point
- Provide new spatial origin via header keywords
- Feed cubes into `gemcube`



Merge Data Cubes

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- Provide new spatial origin via header keywords
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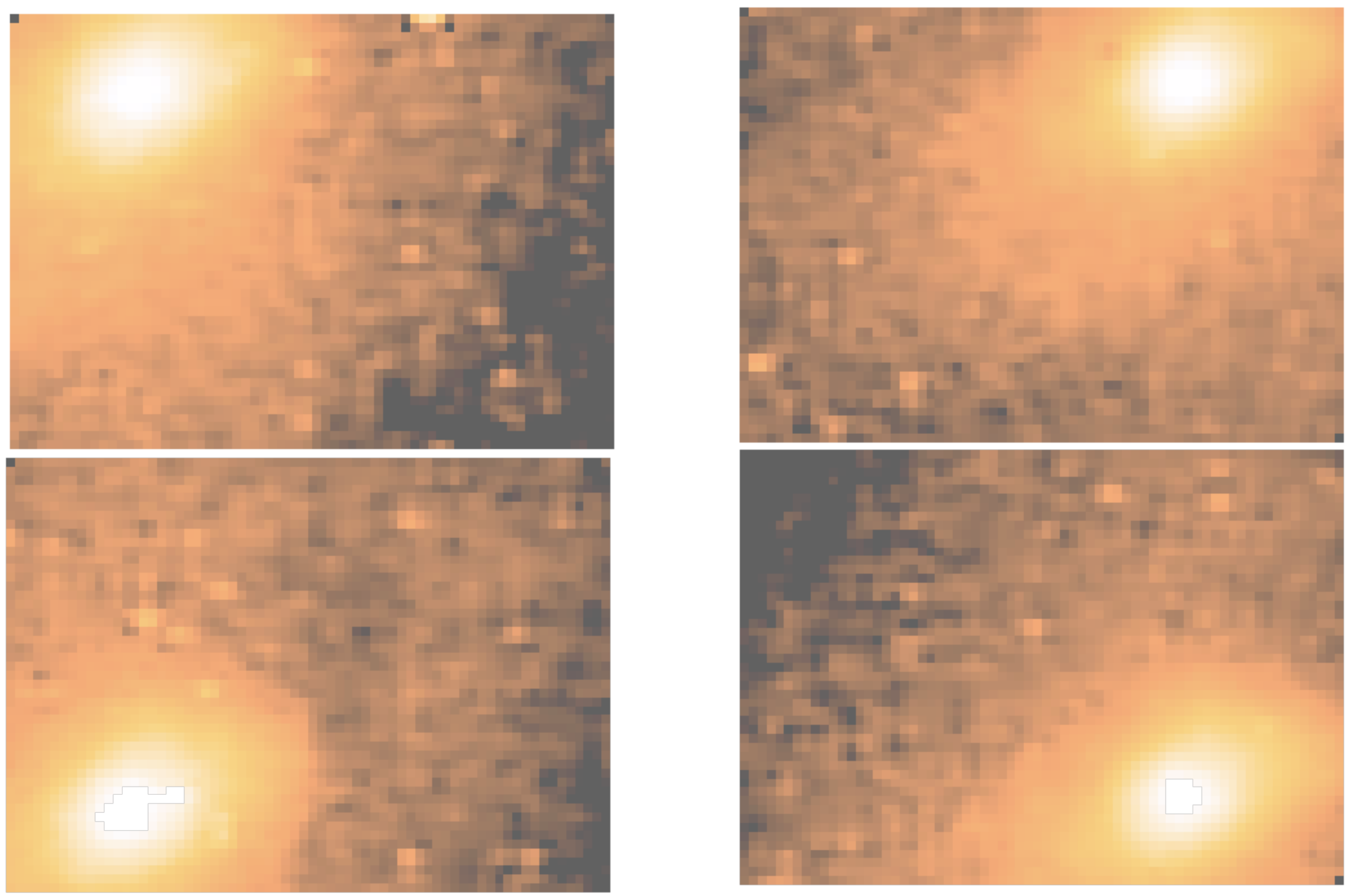

Merge Data Cubes

- Create 3D cubes and inspect image planes via ds9
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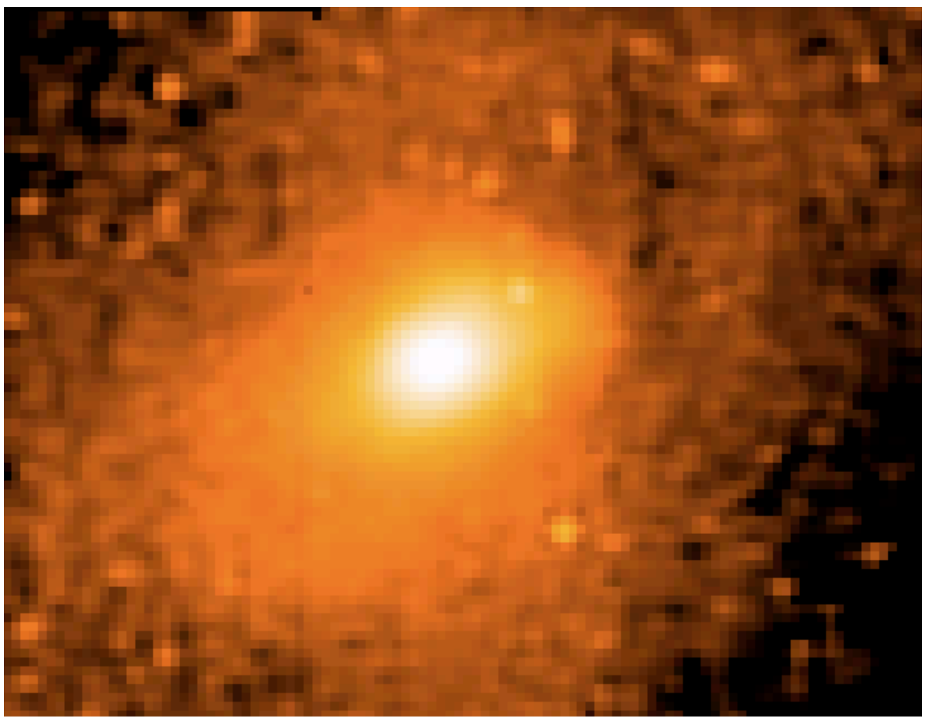
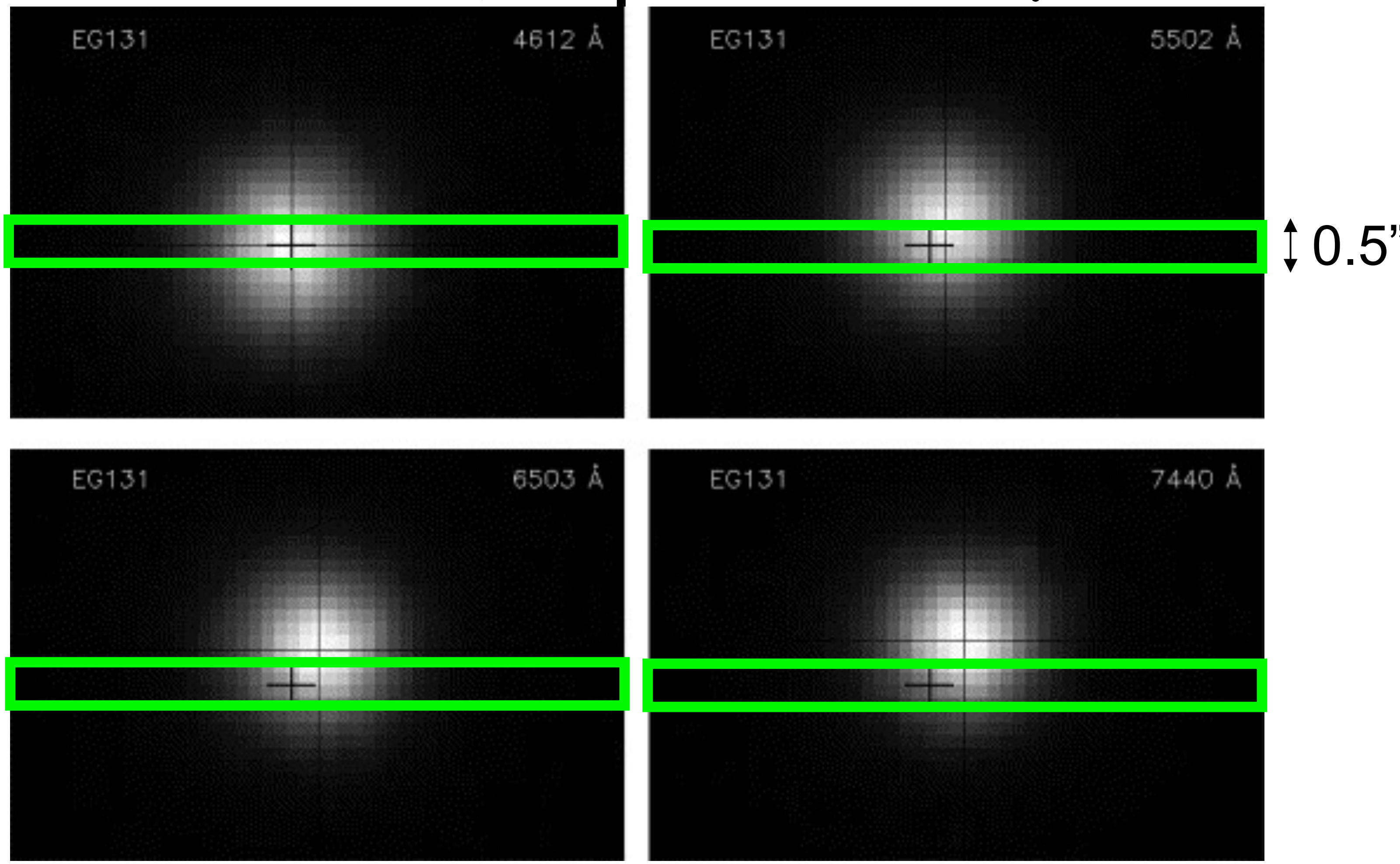
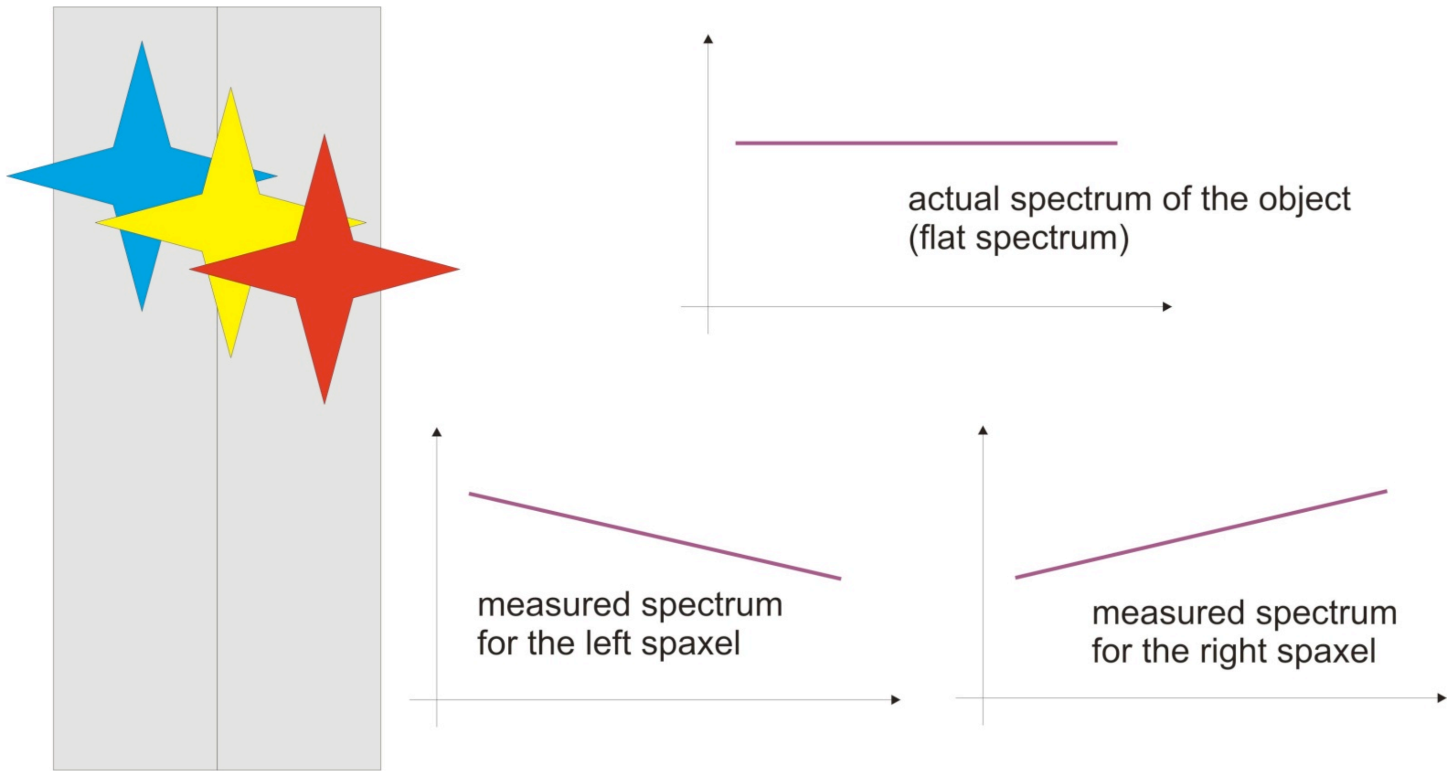


Extras: Atmospheric Refraction



- Atmospheric refraction = image shifts as function of wavelength
- Shifts largest at blue wavelengths
- Can be corrected during reduction by shifting back each λ plane
- Convenient to do this during merging (interpolating anyway…)

Extras: Atmospheric Refraction



- Spectral slope can appear to change between spaxels around the peak
- Can reduce the effect for point sources by extracting 1D spectrum within an aperture covering red and blue flux.

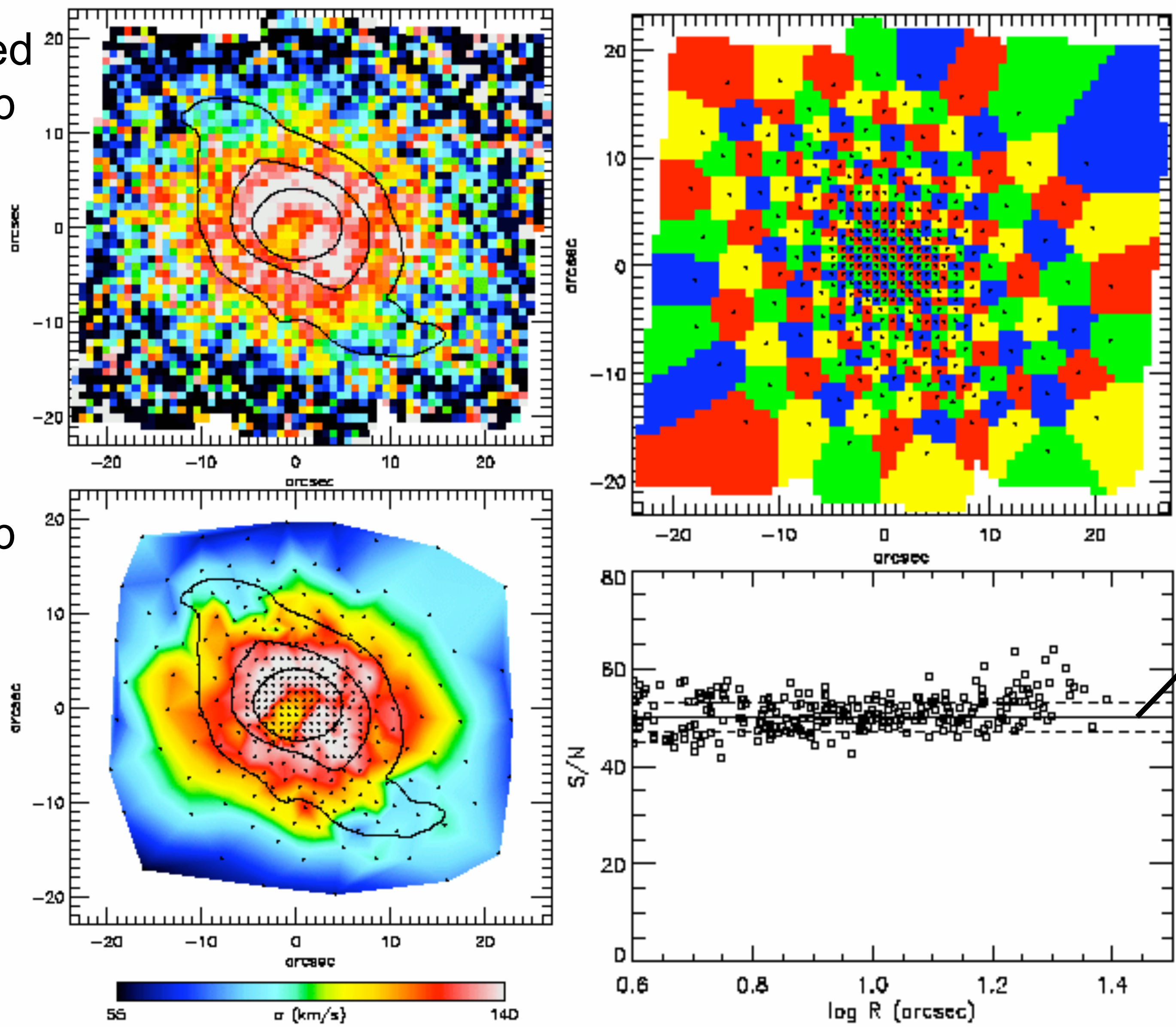
Extras: Spatial Binning

Unbinned S/N map

Voronoi tessellation

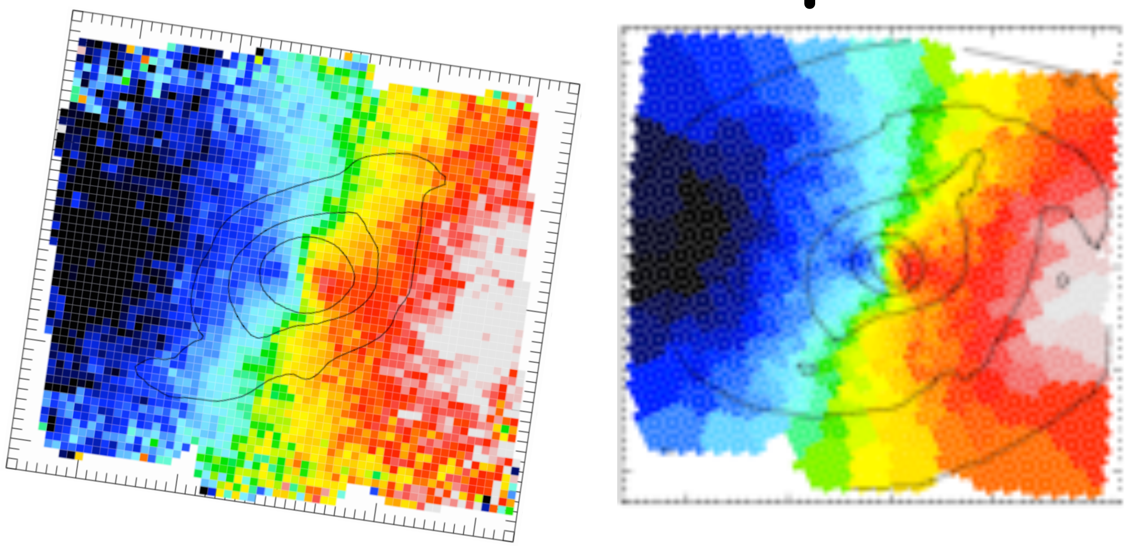
S/N map After binning

Target S/N



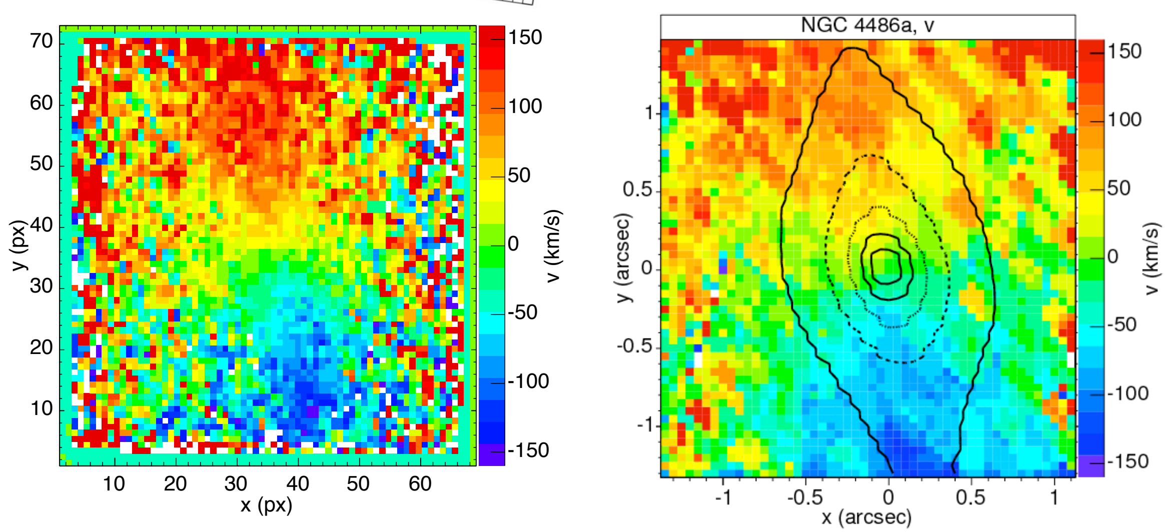
Cappellari & Copin 2003

Extras: Spatial Binning



SAURON data
on NGC 2273

Falcon-Barroso et al.



SINFONI data
on NGC 4486a

Nowak et al.