Gemini Multi-Object Spectrograph
GMOS

- GMOS Overview
- Data Reduction:
  - Imaging (R. Carrasco)
  - Longslit spectroscopy (R. Schiavon)
  - MOS spectroscopy (R. Schiavon)
  - Nod & Shuffle spectroscopy (R. Schiavon)
  - IFU (R. Carrasco)

Rodrigo Carrasco
Gemini Observatory
SGDW, São José dos Campos
27 – 30 October 2011

Winter at Cerro Pachón

GMOS Overview

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µm ... ng

- T
- G
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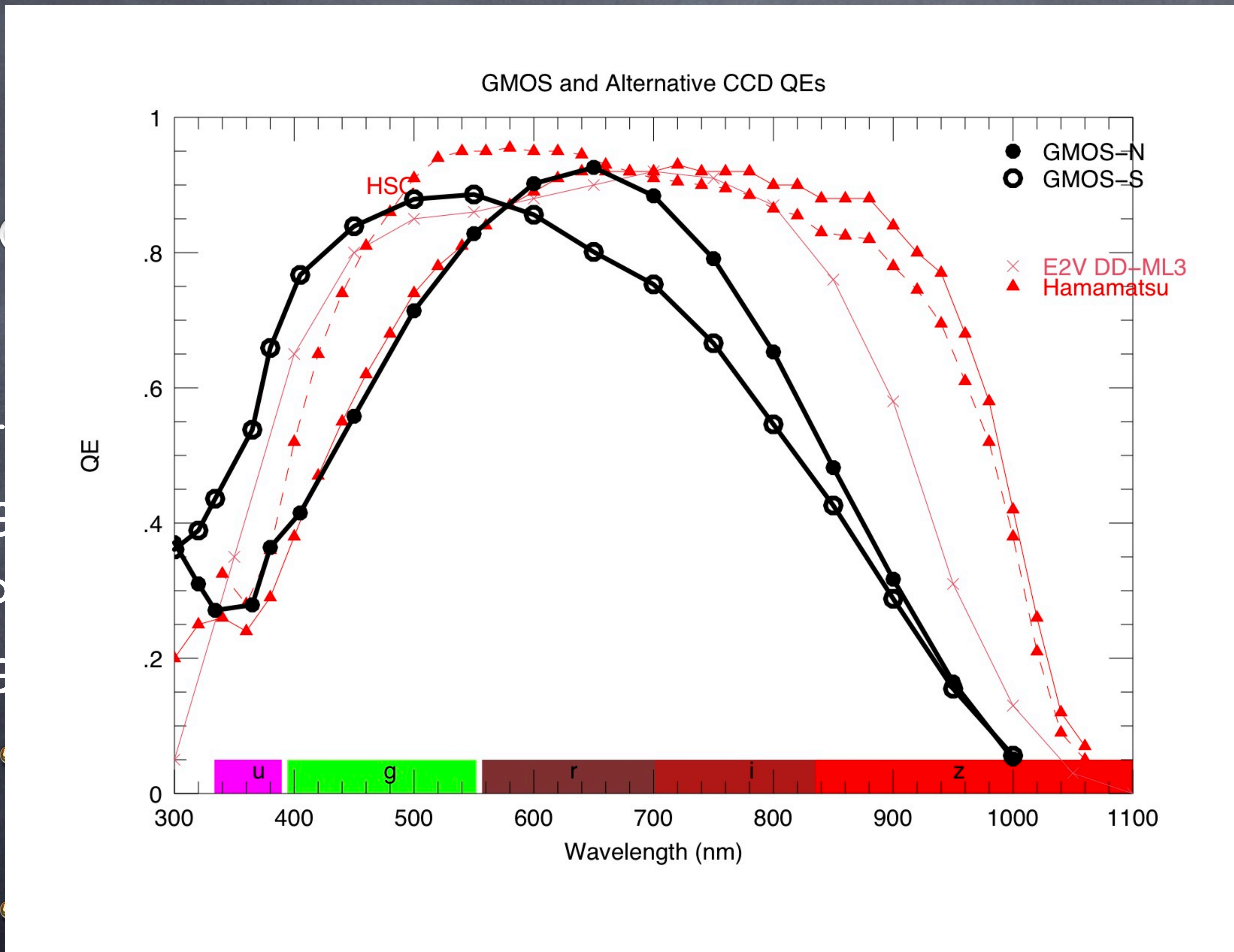
- G
  - ... lly



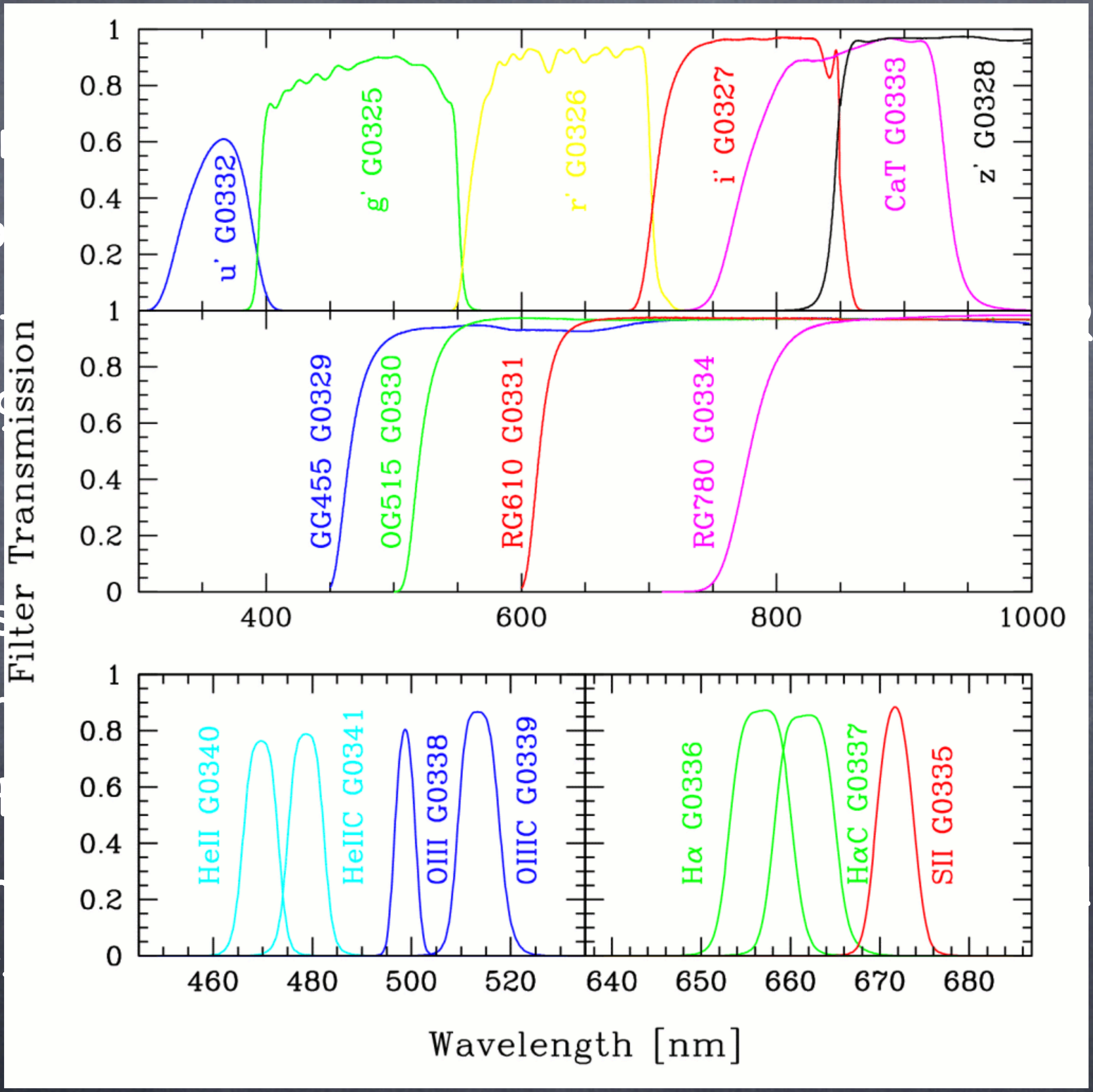
GMOS Overview

- Broad ba
- Narrow b SII
- Blocking RG610,

RG780, DS

- Long-slits
- Custom m
- Integral
- Nod & Sh and

micro-shuf



GMOS Overview

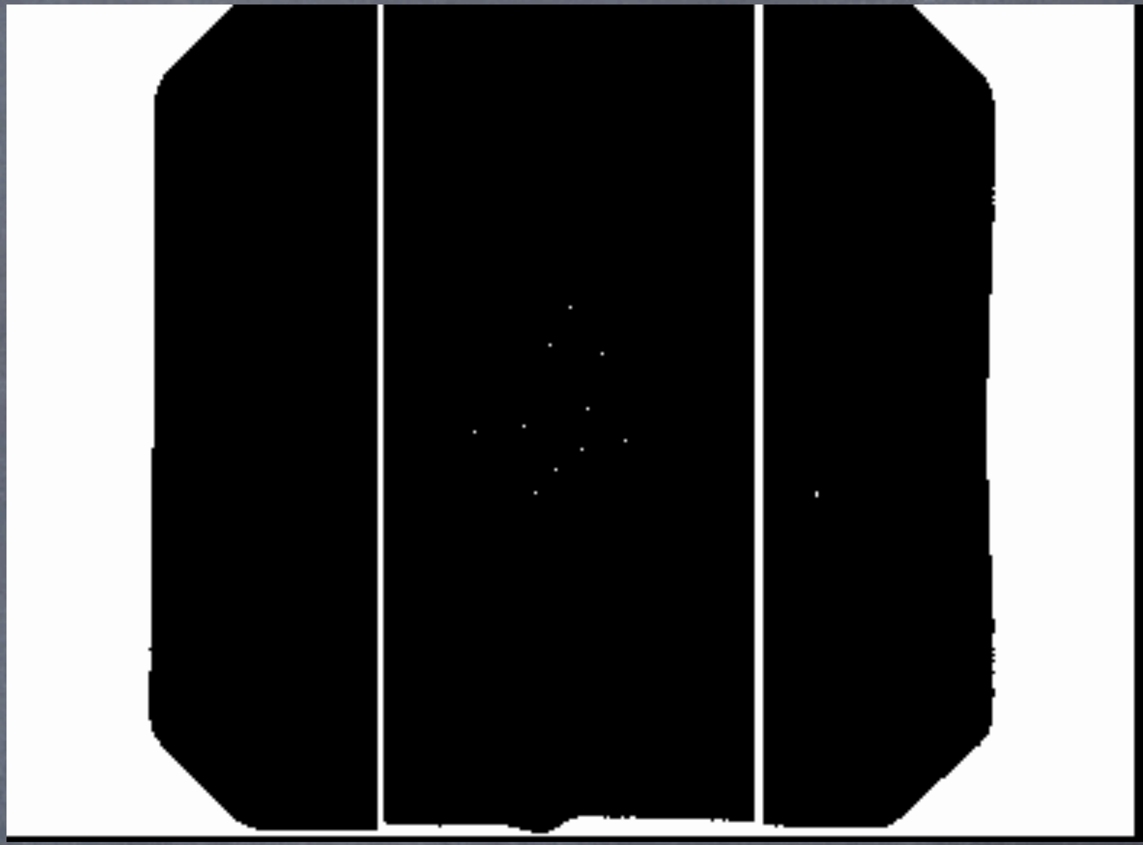
- Available gratings

Grating	Blaze wav. [Ang]	R (0.5″ LS)	Coverage [Ang.]	Dispersion [Ang/pix]
B1200	4630	3744	1430	0,23
R831	7570	4396	2070	0,34
R600	9260	3744	2860	0,45
R400	7640	1918	4160	0,47
B600	4610	1688	2760	0,67
R150	7170	631	10710	1,74

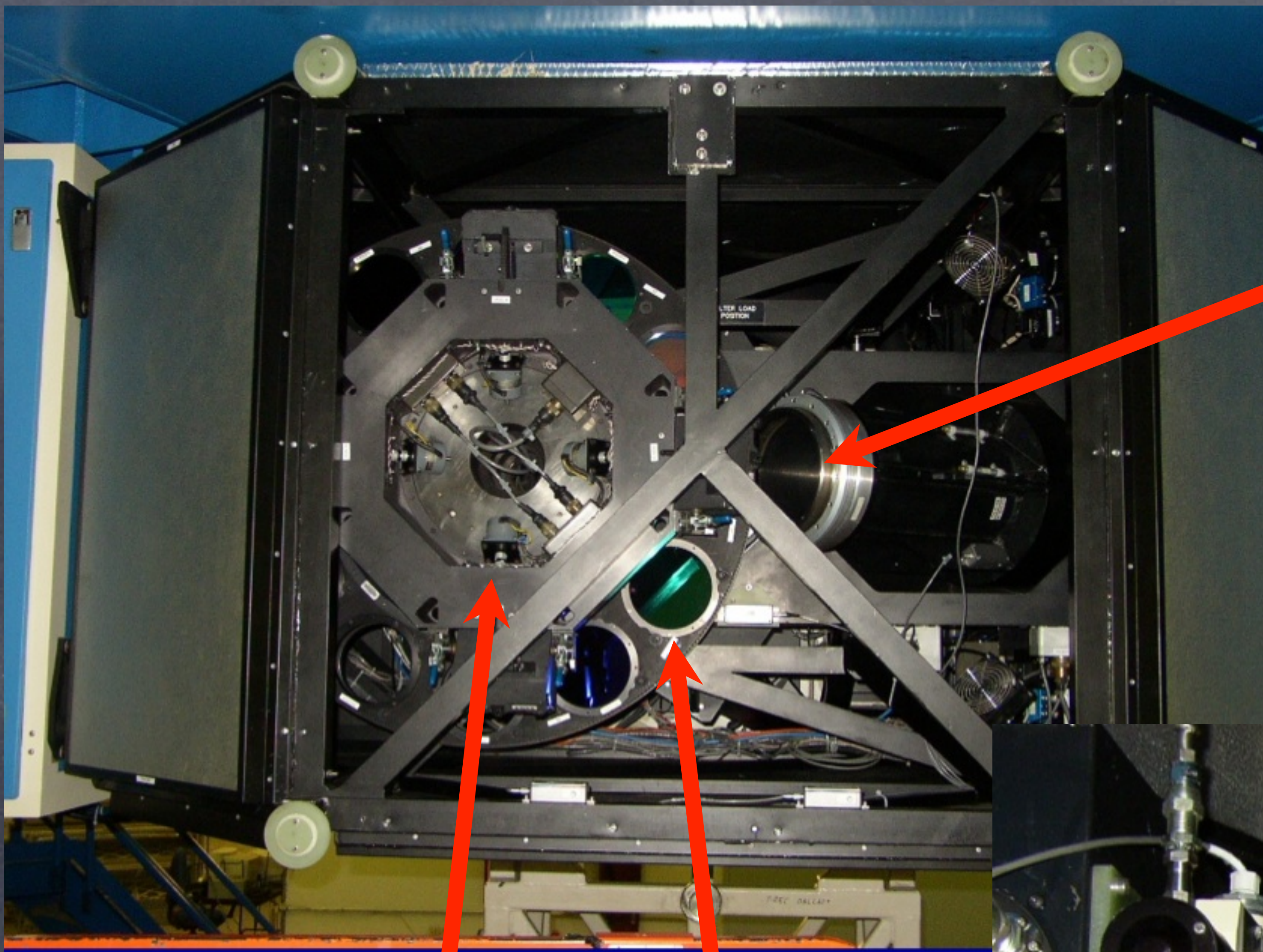
Grating turret supports only 3 gratings + mirror

GMOS Overview

- GMOS detectors characteristics
  - Good cosmetic, with only few bad pixels
  - Bad pixels masks for imaging - provided by the observatory (1x1 and 2x2) - gmos$data/ directory
- Saturation level: ~64000 ADU and linearity ~60.000 ADU (<1%)
- CCD readouts and gains configurations
  - Slow readout/low gain (science)
  - Fast readout/low gain (bright obj.)
  - Fast readout/high gain
  - Slow readout/high gain (eng. only)
- Readout time (full frame):
  - 1x1 slow/low ~ 140 sec
  - 2x2 slow/low ~ 45 sec

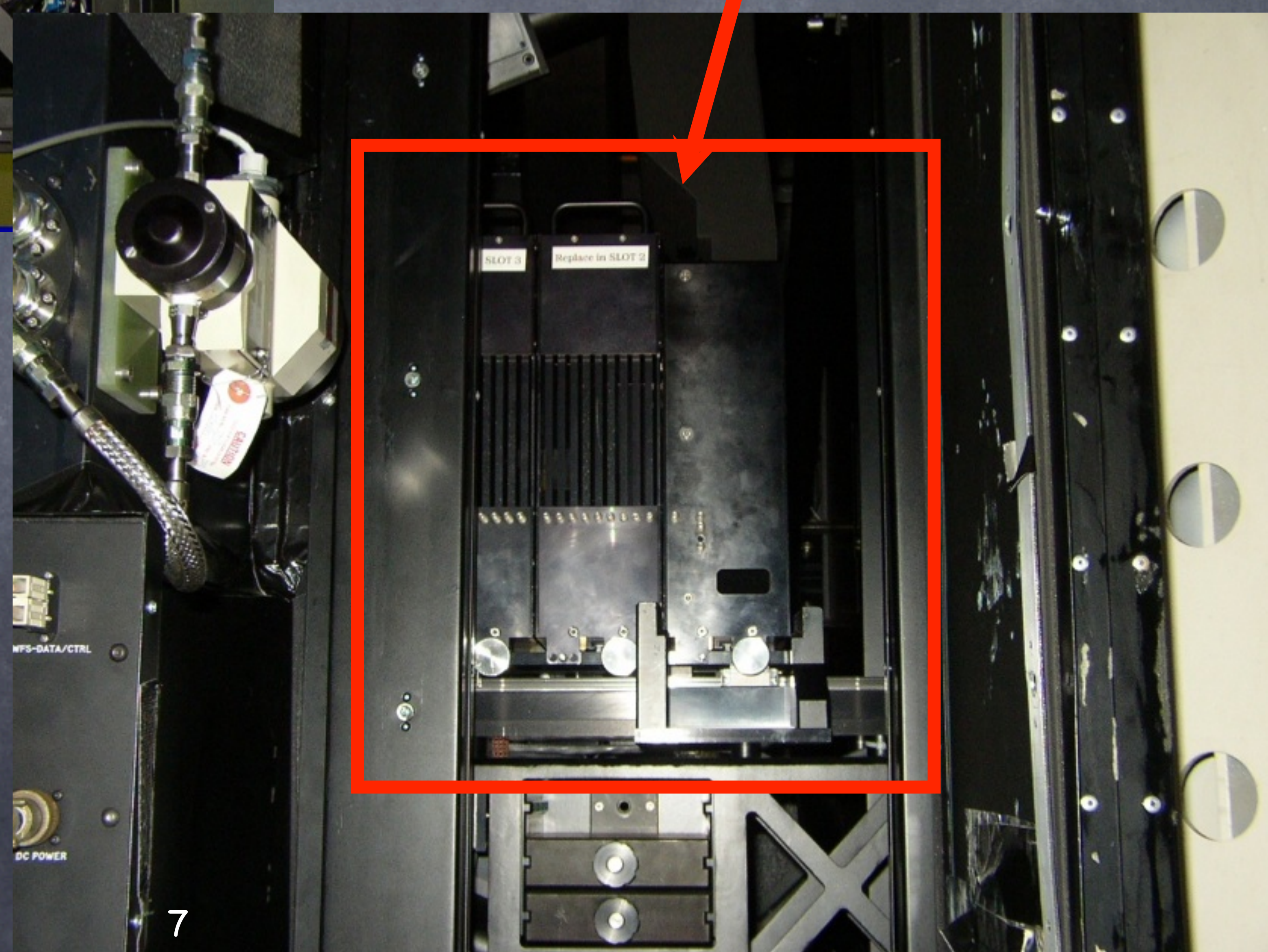


SDSU Gain number			1 (High)		2 (Low)		5 (High)		6 (Low)	
CCD	Rate	Amp	Gain	Noise	Gain	Noise	Gain	Noise	Gain	Noise
1	F	L					5.054	6.84	2.408	4.49
1	F	R					5.253	6.54	2.551	5.07
1	S	L	4.954	5.70	2.372	3.98				
1	S	R	4.862	5.19	2.403	4.01				
2	F	L					5.051	7.35	2.295	4.42
2	F	R					4.954	11.37	2.288	5.03
2	S	L	4.532	4.81	2.076	3.85				
2	S	R	4.592	4.96	2.131	3.83				
3	F	L					4.868	8.56	2.264	4.63
3	F	R					4.833	7.88	2.260	4.09
3	S	L	4.381	4.81	2.056	3.27				
3	S	R	4.411	4.34	2.097	3.16				
Ave	F						5.002	8.09	2.344	4.622
Ave	S		4.622	4.968	2.189	3.683				



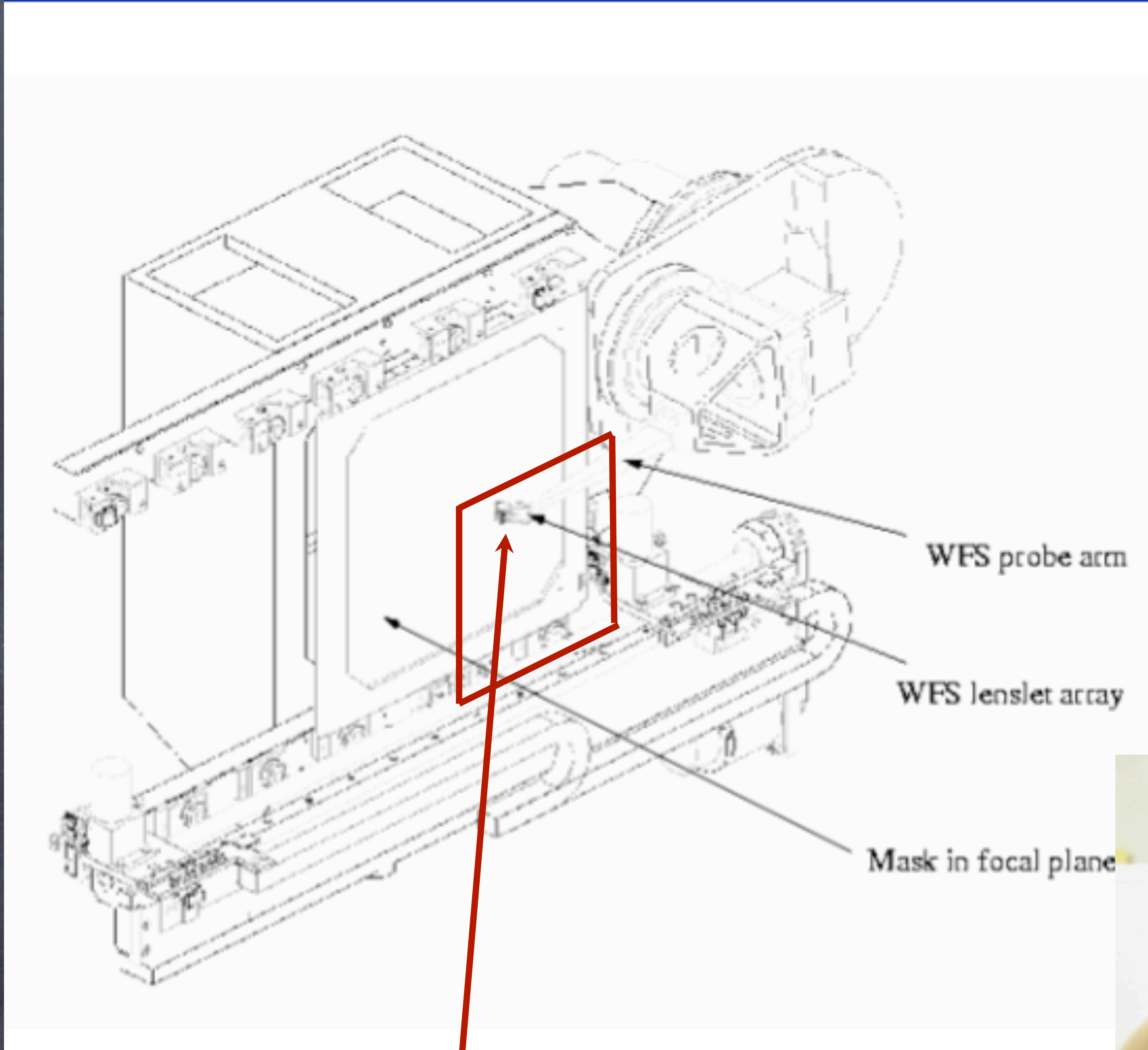
to the detector

Mask assembly with cassettes and masks



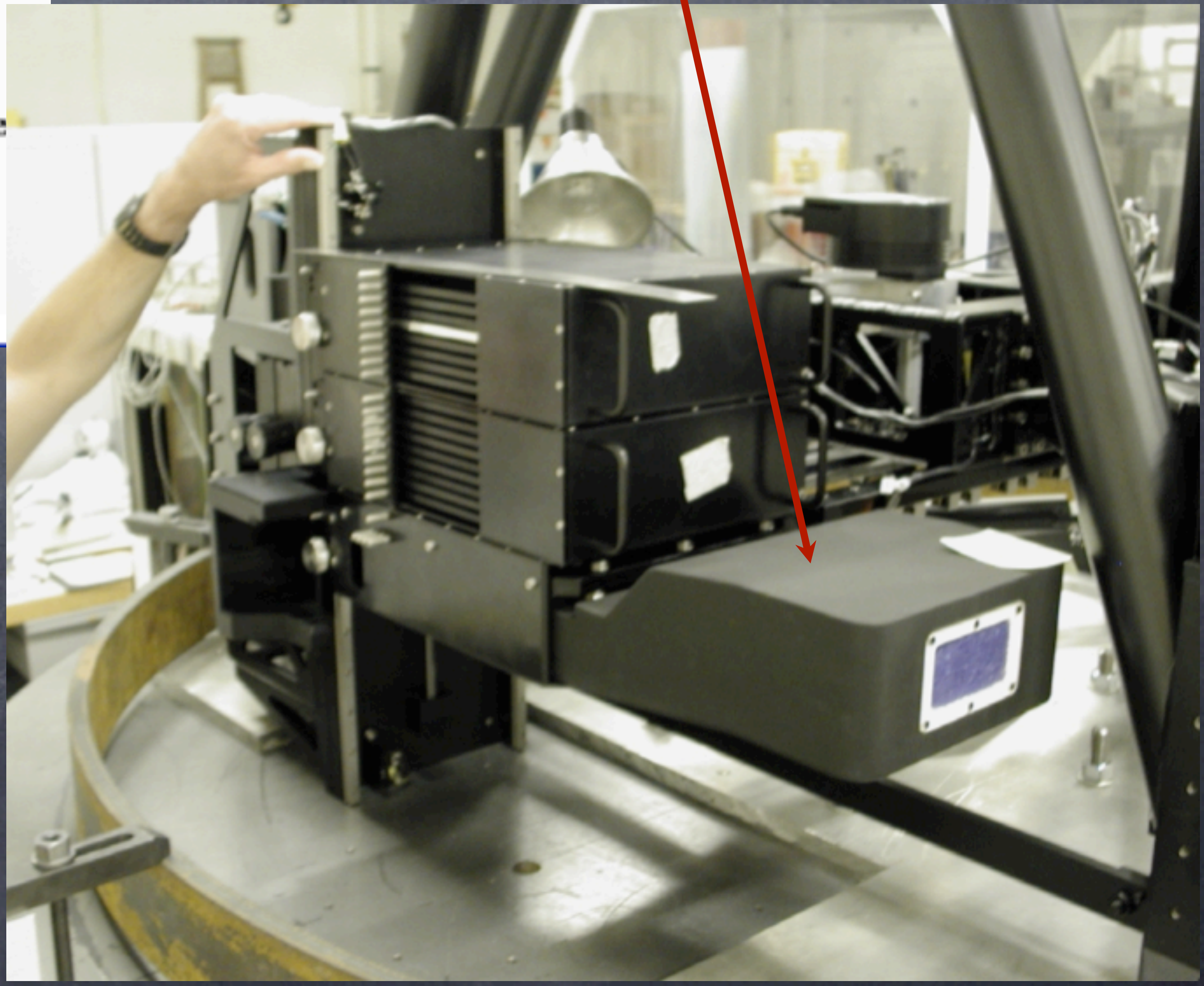
Grating turret

Filter wheels



OIWFS and patrol field area

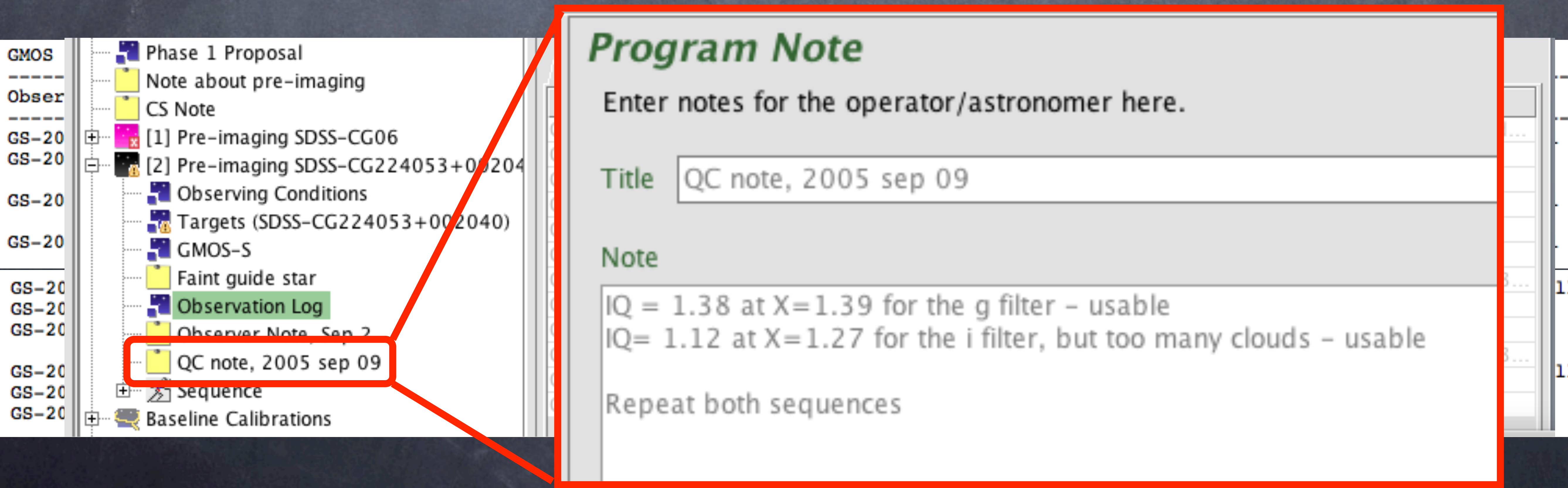
Integral Field Unit
Cassette # 1



GMOS Images: Data Reduction

General guidelines and suggestions

- Fetch your program using the Observing Tool
- Check the notes added by the observer(s) and/or the Queue Coordinator(s) regarding your observations
- Check the observing log (you can use the OT)



GMOS Images: Data Reduction

Arranging your files: suggestion

Raw data:

calibrations/ - all baseline daytime calibration raw images

science/ - all science data

standards/ - photometric standard stars (nighttime calibrations)

Reductions:

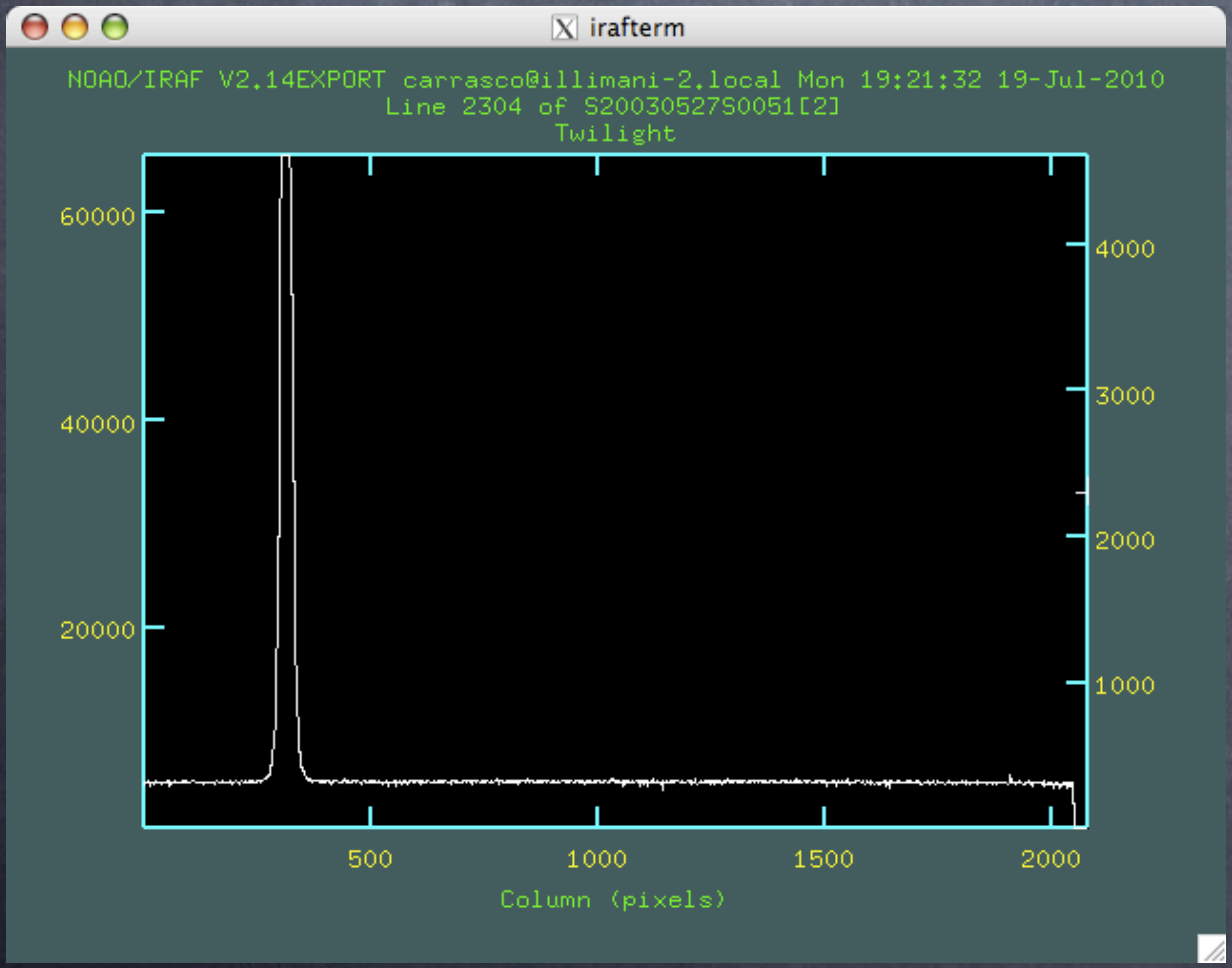
reductions/ - all reductions

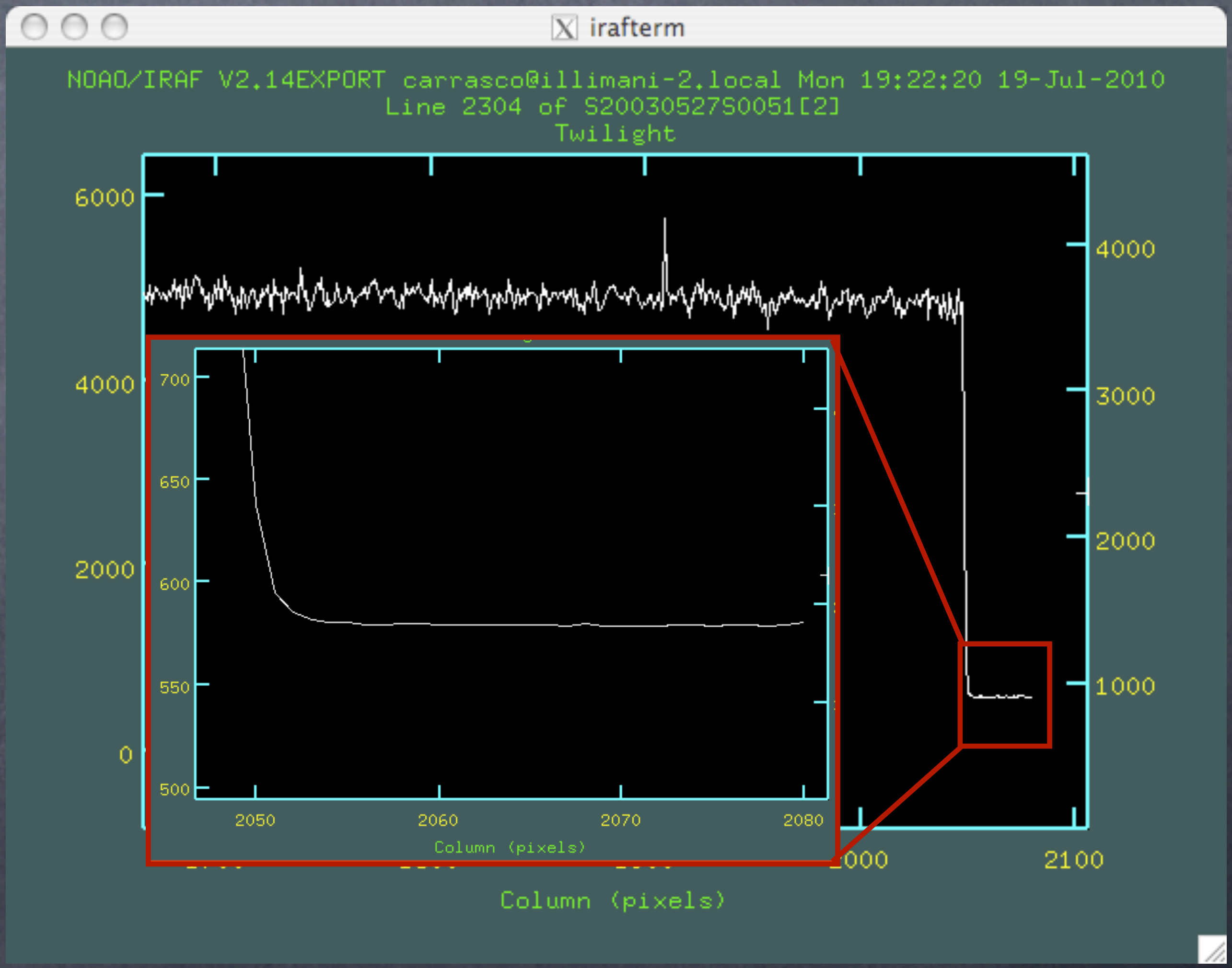
- calibrations/ - reductions of daytime calibrations
- Obj1/ - reduction of the first science object
  - combined/ - combined images
  - photstd/ - reductions of phot. Std.
- Obj2/ - reduction of the second science object

GMOS Images: Data Reduction

General guidelines and suggestions

- Inspect all images (bias, twilight flats, science images) using your favorite tools: imstatistic, implot, etc in IRAF, IDL routines, etc.





GMOS Images: Data Reduction

Typical GMOS imaging observations

- Science Observations
  - A sequence of exposure using one or more filters.
  - The sequence normally has offsets to avoid the gaps between CCDs.
- Daytime calibrations (Baseline) – GN(GS)-CALYYYYMMDD
  - Routine Bias for all binning (slow/fast readout, low gain).
  - Routine twilight flats for 2x2 binning (all filters).
  - Processed bias and twilight flats are in the GSA, but not over-scan subtracted
- Nighttime calibrations (Baseline) - GN(GS)-CALYYYYMMDD
  - Photometric standard stars - zero point calibrations
  - Blank fields – fringe correction (i′ and z′ filter only)

GMOS Images: Data Reduction

- Basic IRAF data reduction information in the web.
- Good starting point to reduce your **data**
- http://www.gemini.edu/sciops/data/IRAFdoc/gmosinfoimag.html
- Dataset
  - SV data on Hickson Compact Group 87 from 2003
  - Observations with g', r' and i' filters, 1 x 1 (no binning)
  - Offsets between exposures to avoid gaps

```
# Reducing HCG87
#157-159 HGC87          g      -      -          300
#161-163 HGC87          r      -      -          180
#164-169 HGC87          i      -      -          120
```

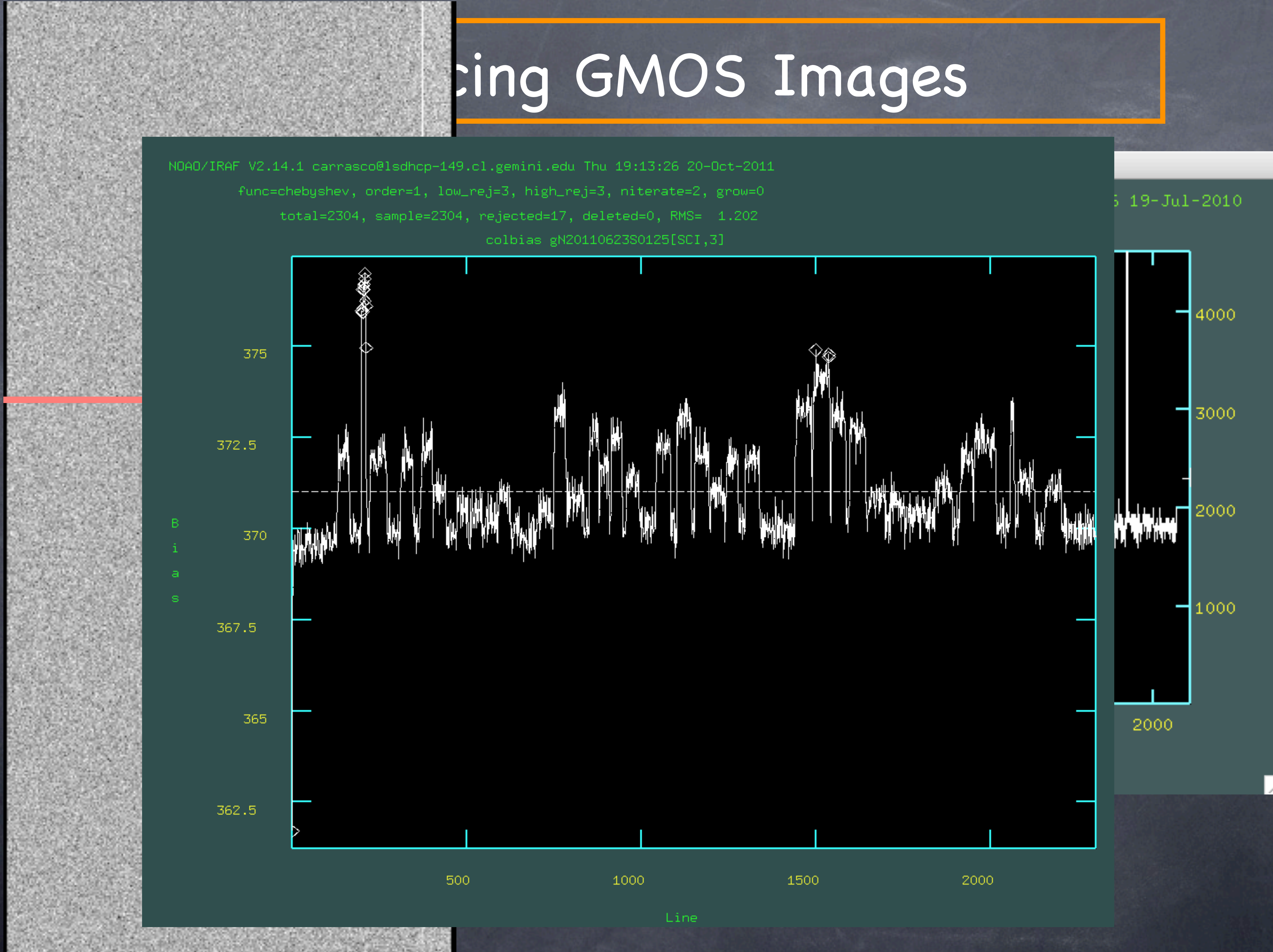
```
# Bias
# GS-CAL20030525-2    10:37  212-221 Bias     -      -           -  1    1x1,full/slow/low

# Twilight flats
# GS-CAL20030527-3   22:15  39-48   Twilight g  -  -  5,5,7,20,35,50   1x1,full,slow,low,best
# GS-CAL20030530-6   22:38  45-47   Twilight r  -  -                   1x1,full,slow,low,best
# GS-CAL20030527-4   22:38  49-52   Twilight i  -  -  30,80,120,160    1x1,full,slow,low,best

# Blank field - fringing correction
# GS-CAL20030525-10   9:15 173-177  Blank21h i  -  -             180   1x1,full,slow,low,best
```

GMOS Images: Data Reduction

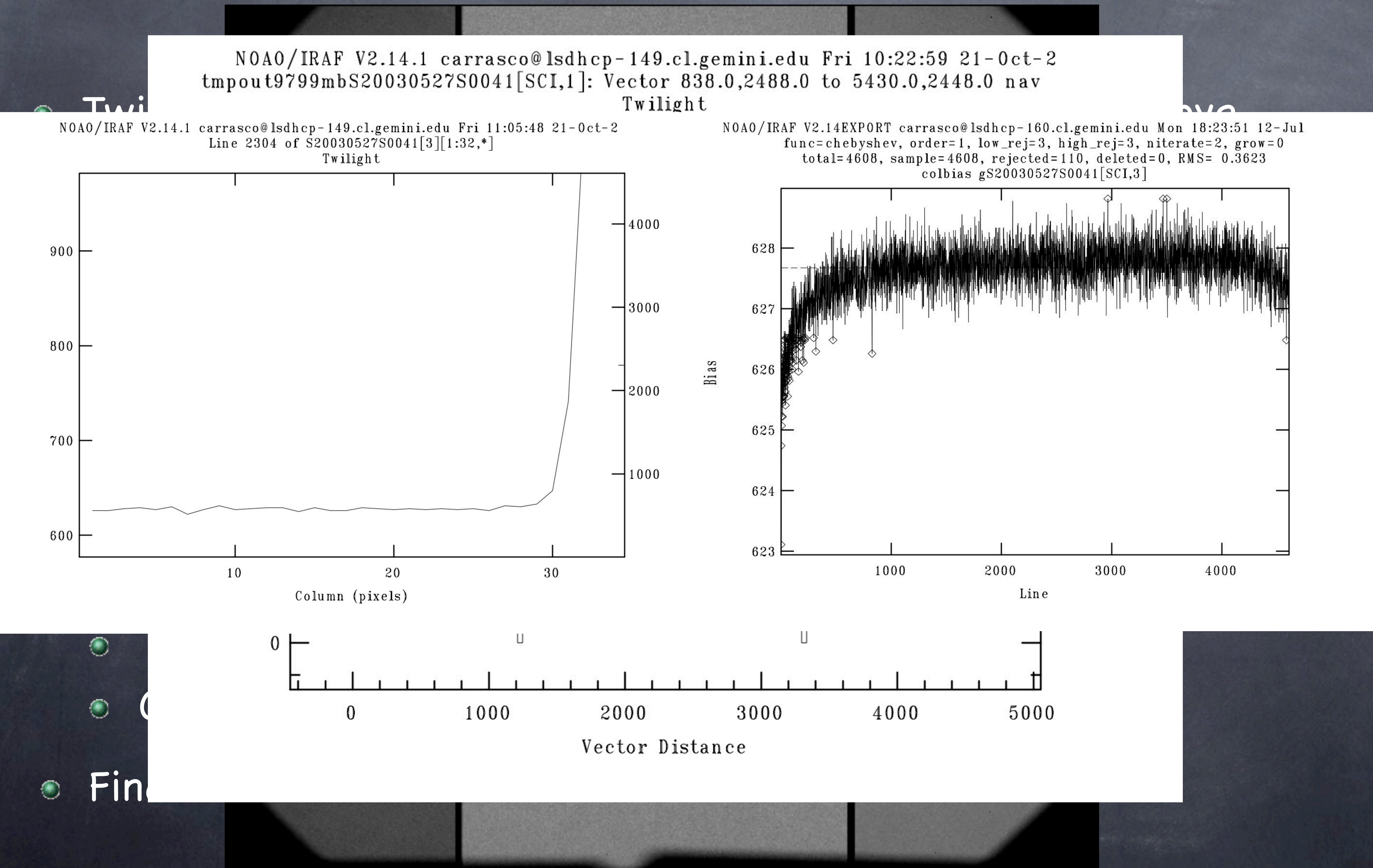
Reduction Steps

- Combine bias (trim, overscan)
- Twilight flats : over-scan, bias subtraction, trim and combine the frames
- Science images: bias and over-scan subtraction, trim and flat-field the frames
- Blank fields to construct a combined image for fringing correction (i'-band only)
- Mosaic the images and combine the frames by filter

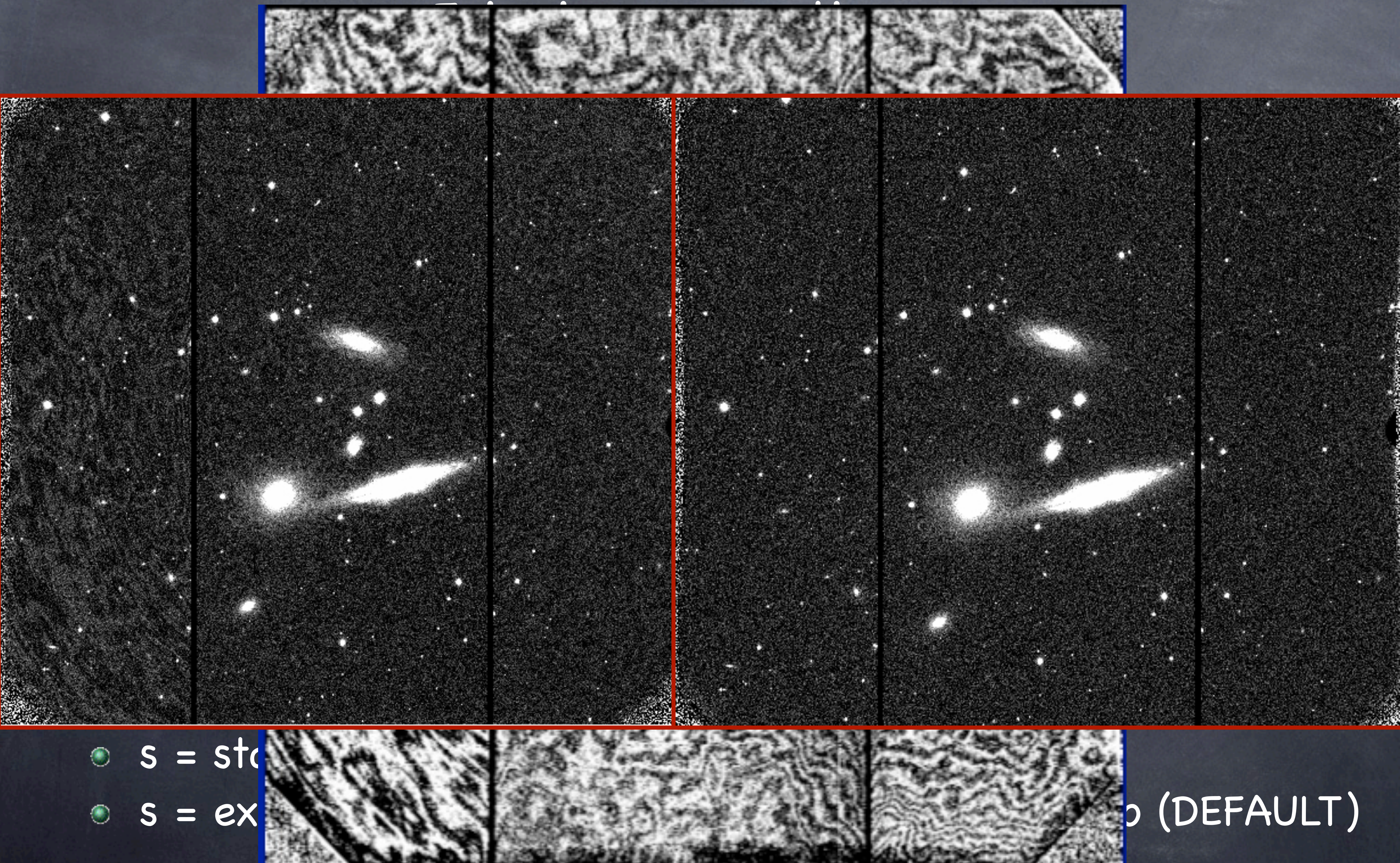
cing GMOS Images



Reducing GMOS Images



Reducing GMOS Images



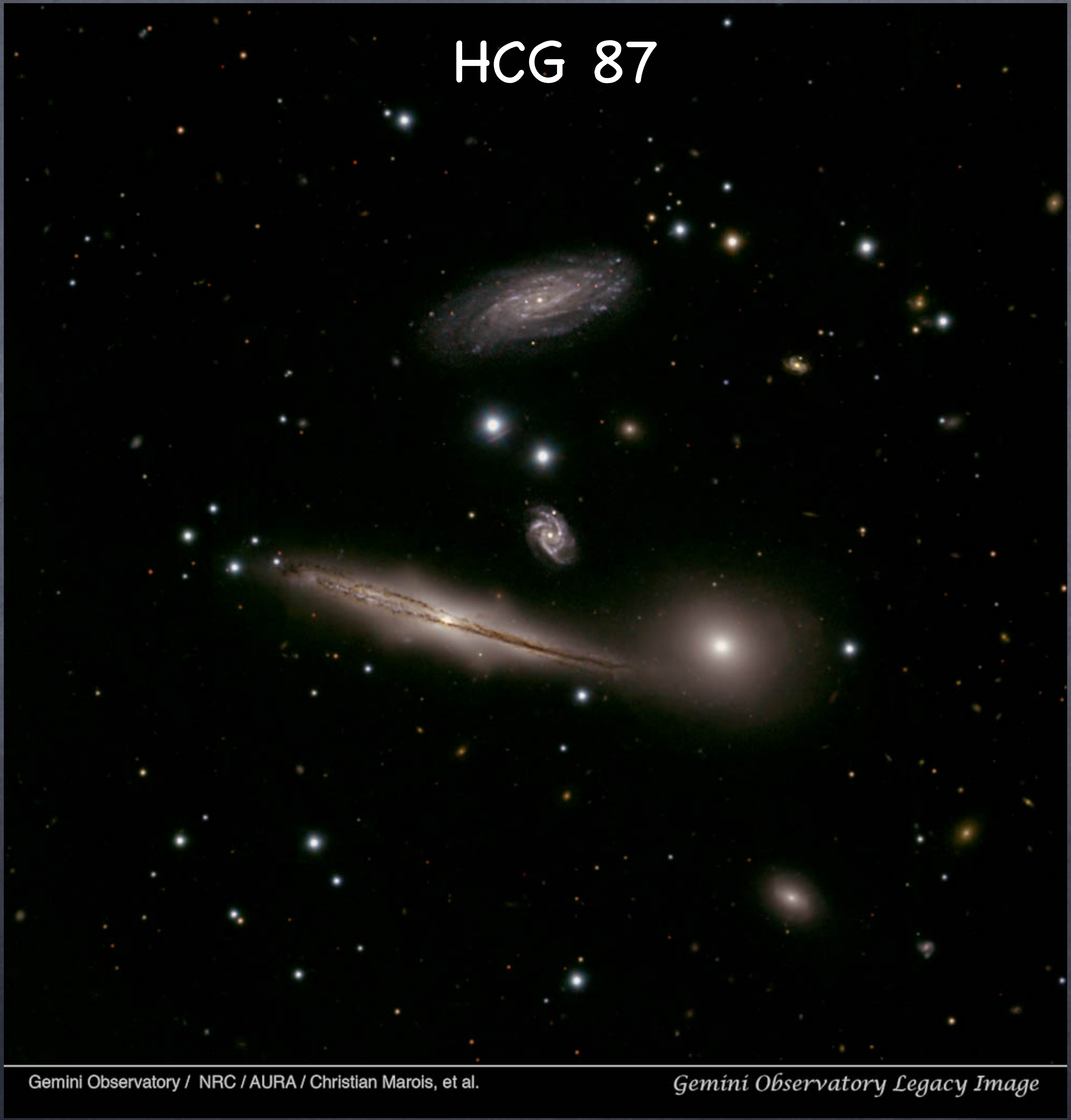
- s = st
- s = ex (DEFAULT)

Reducing GMOS Images

Science images

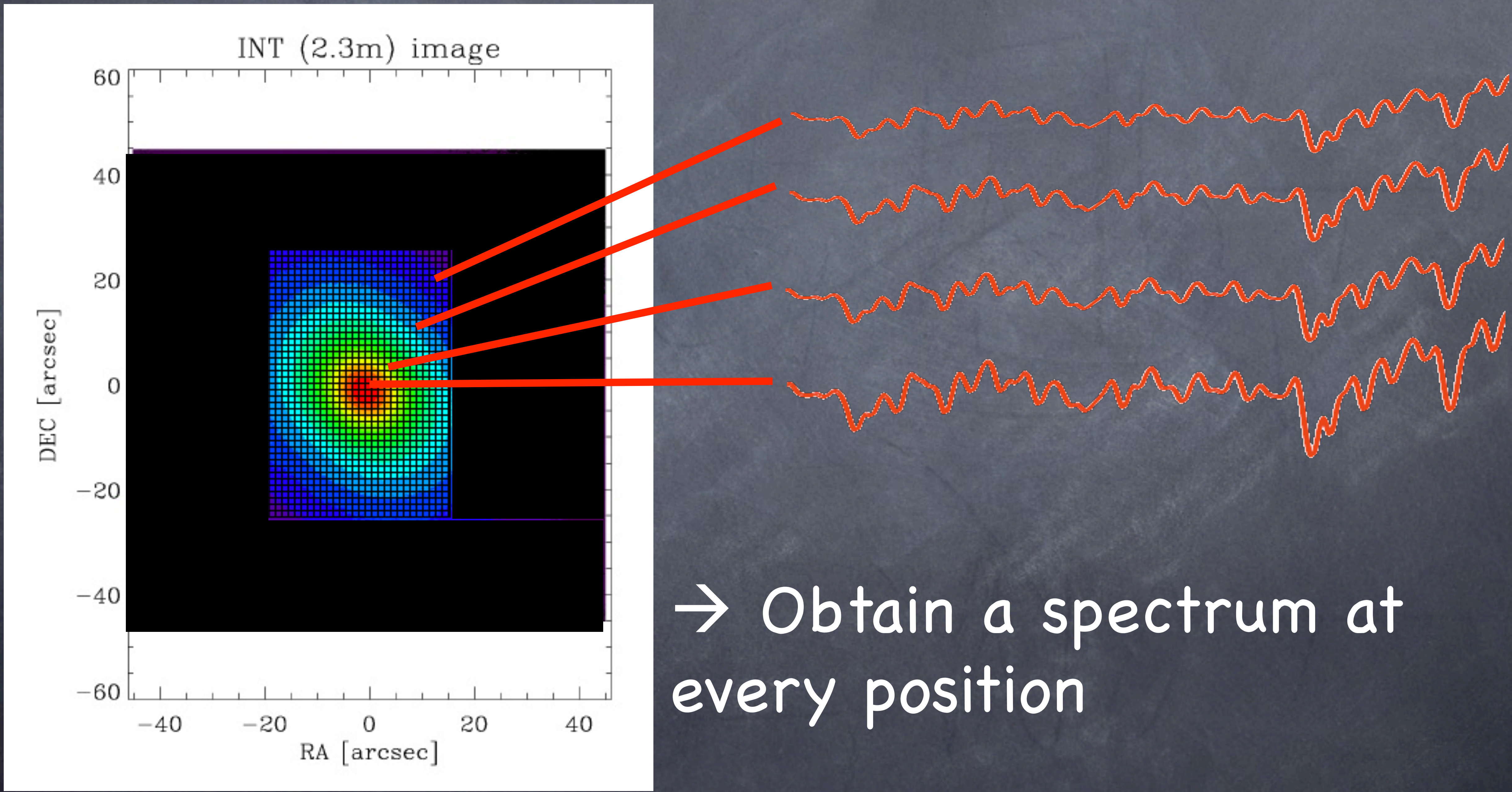
- Reducing the images with gireduce
    - gireduce: gprerare, bias, overscan and flatfield the images
    - gireduce @obj.lst fl_bias+ fl_trim+ fl_flat+ fl_over+ bias=bias.fits flat1=flatg flat2=flatr flat3=flati rawpath=dir$
- Removing fringing with girmfringe (i' band images only)
- Inspect all images with "gdisplay"
- Mosaicing the images with gmosaic - > gmosaic @redima.lst
- Combining your images using imcoadd
- imcoadd - search for objects in the images, derive a geometrical trasformation (shift, rotation, scaling), register the objects in the images to a common pixel position, apply the BPM, clean the cosmic ray events and combine the images

Final GMOS image



GMOS IFU Reduction

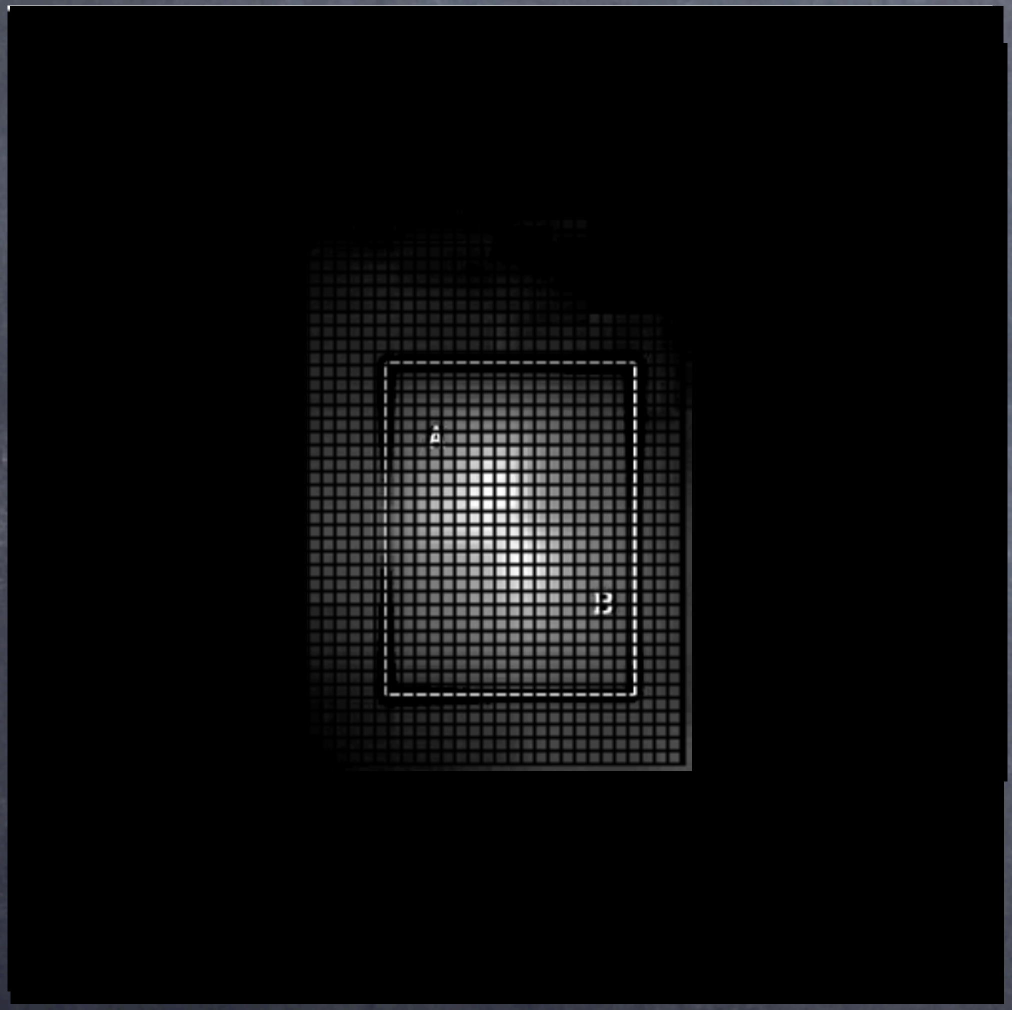
Integral-Field Spectroscopy



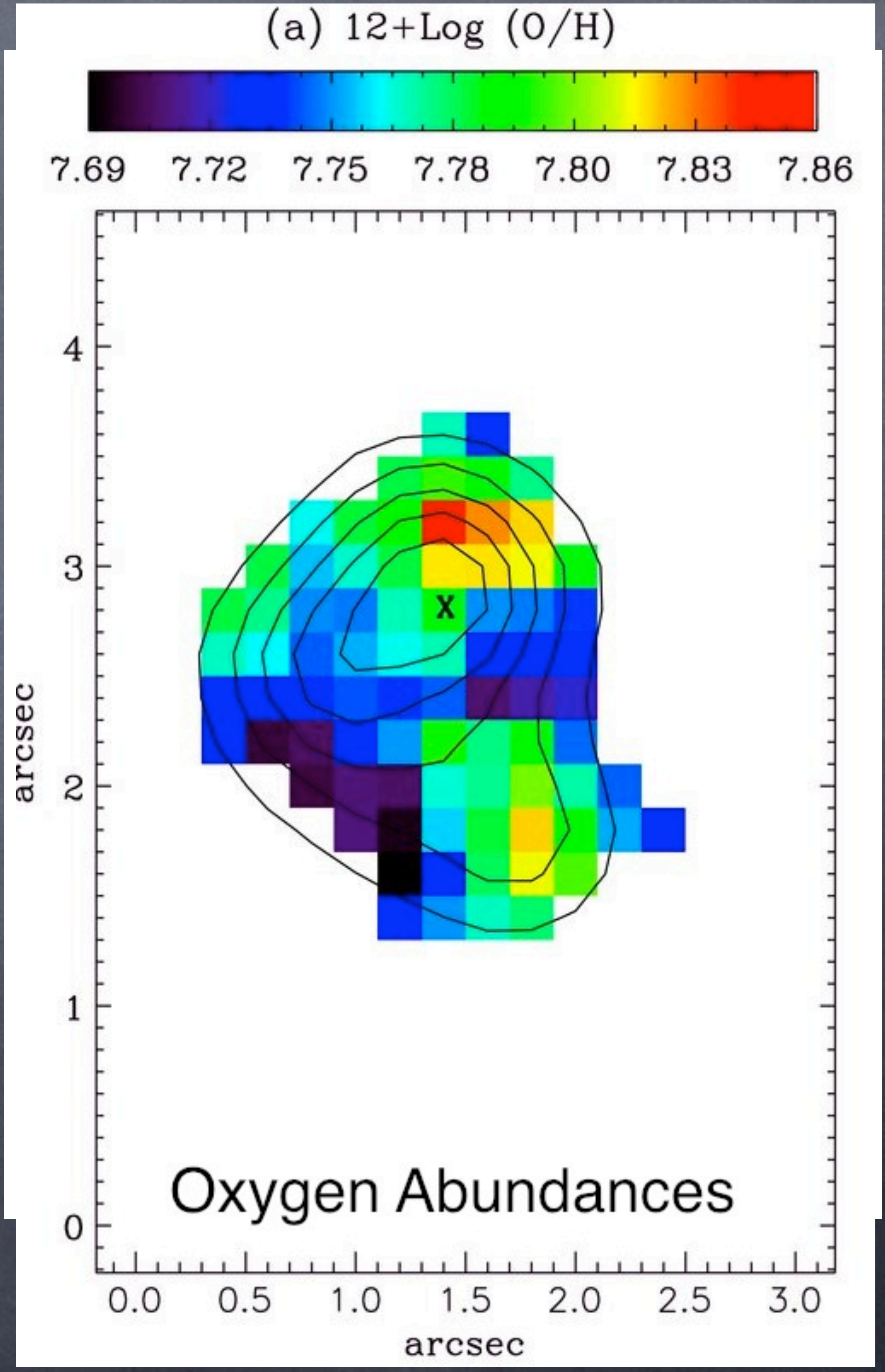
→ Obtain a spectrum at every position

Integral Field Spectroscopy

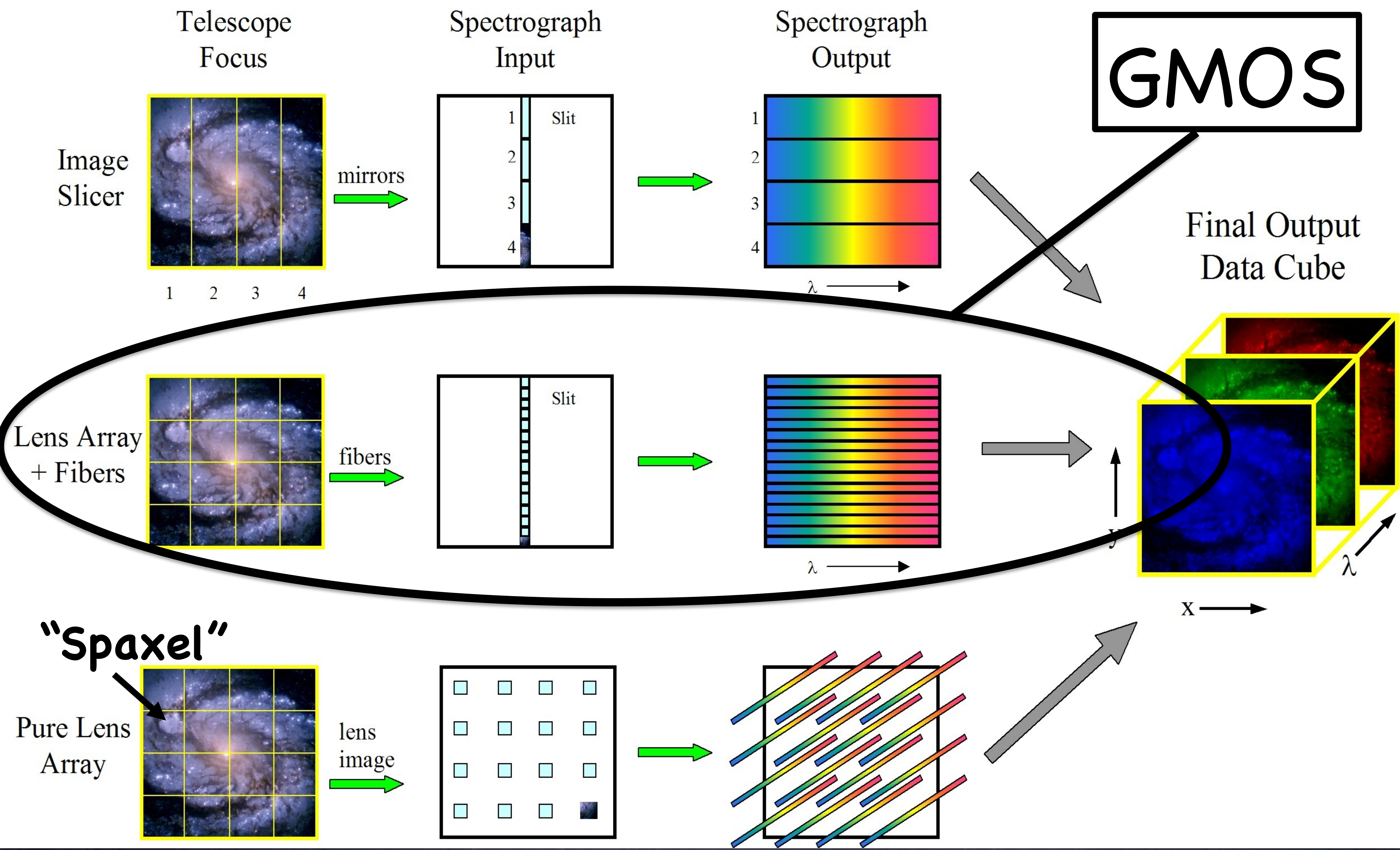
Each spectrum gives



Lagos et al. (2009)

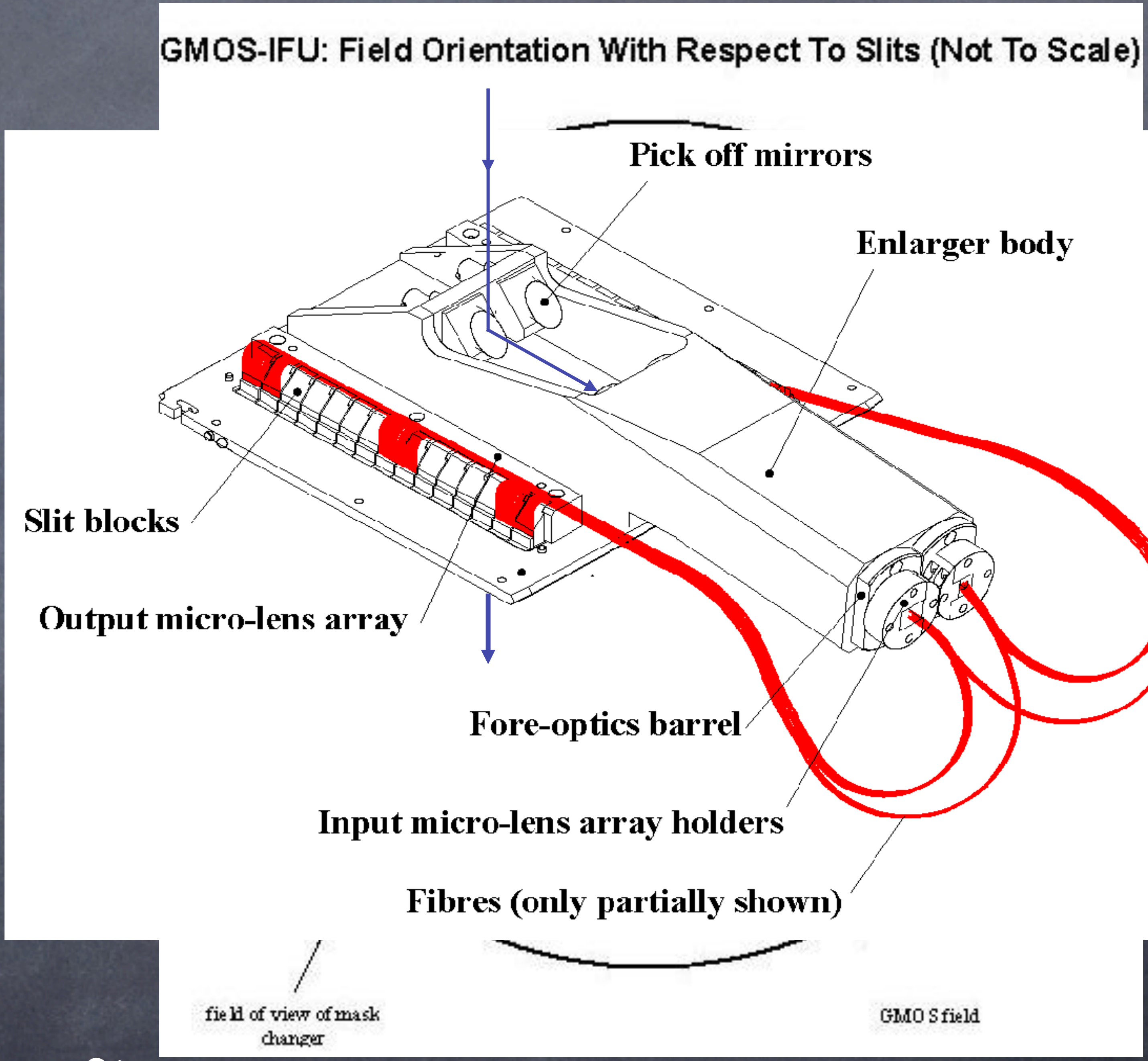


IFU Zoo: How to map 3D on 2D

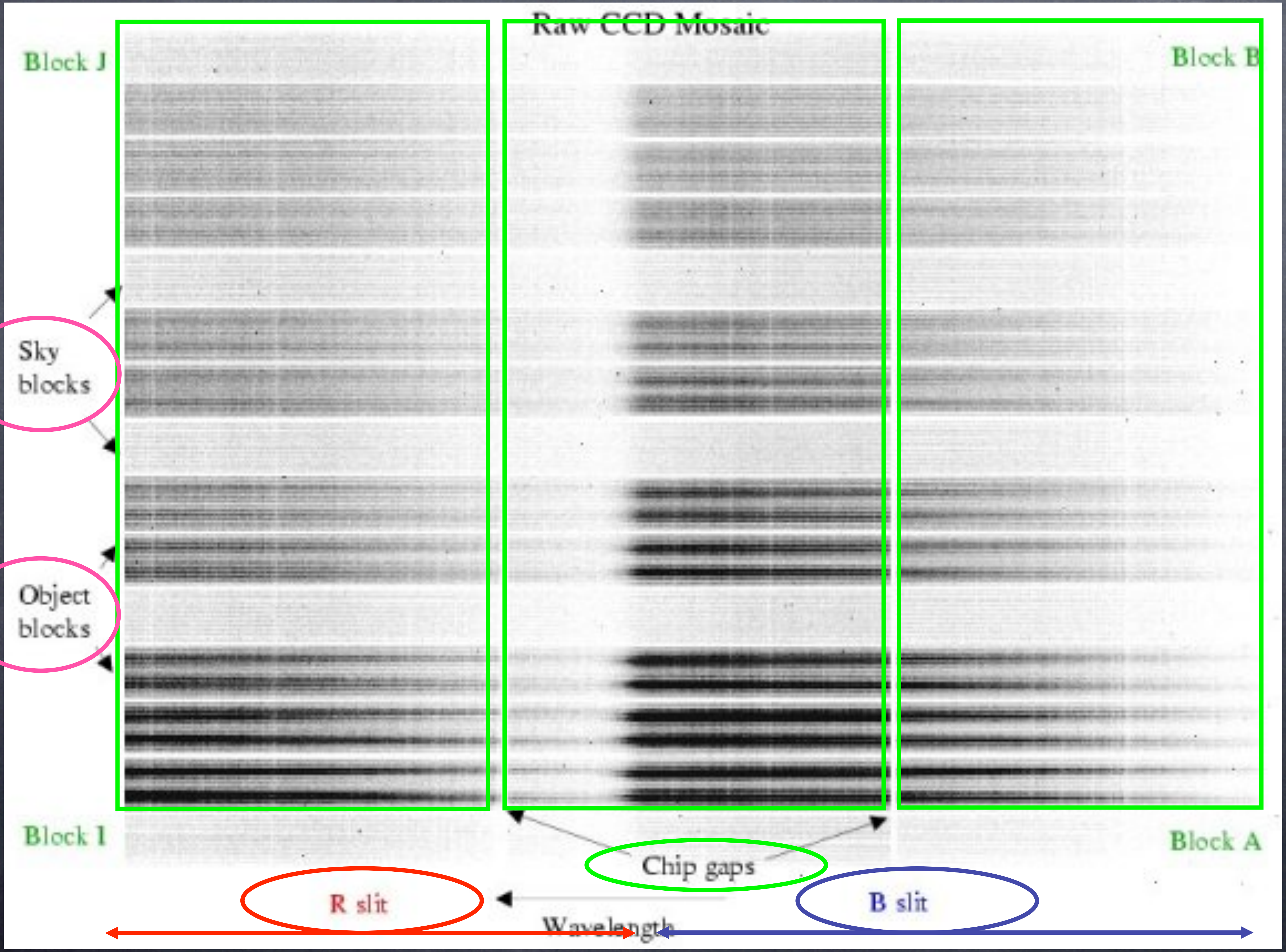


GMOS IFU

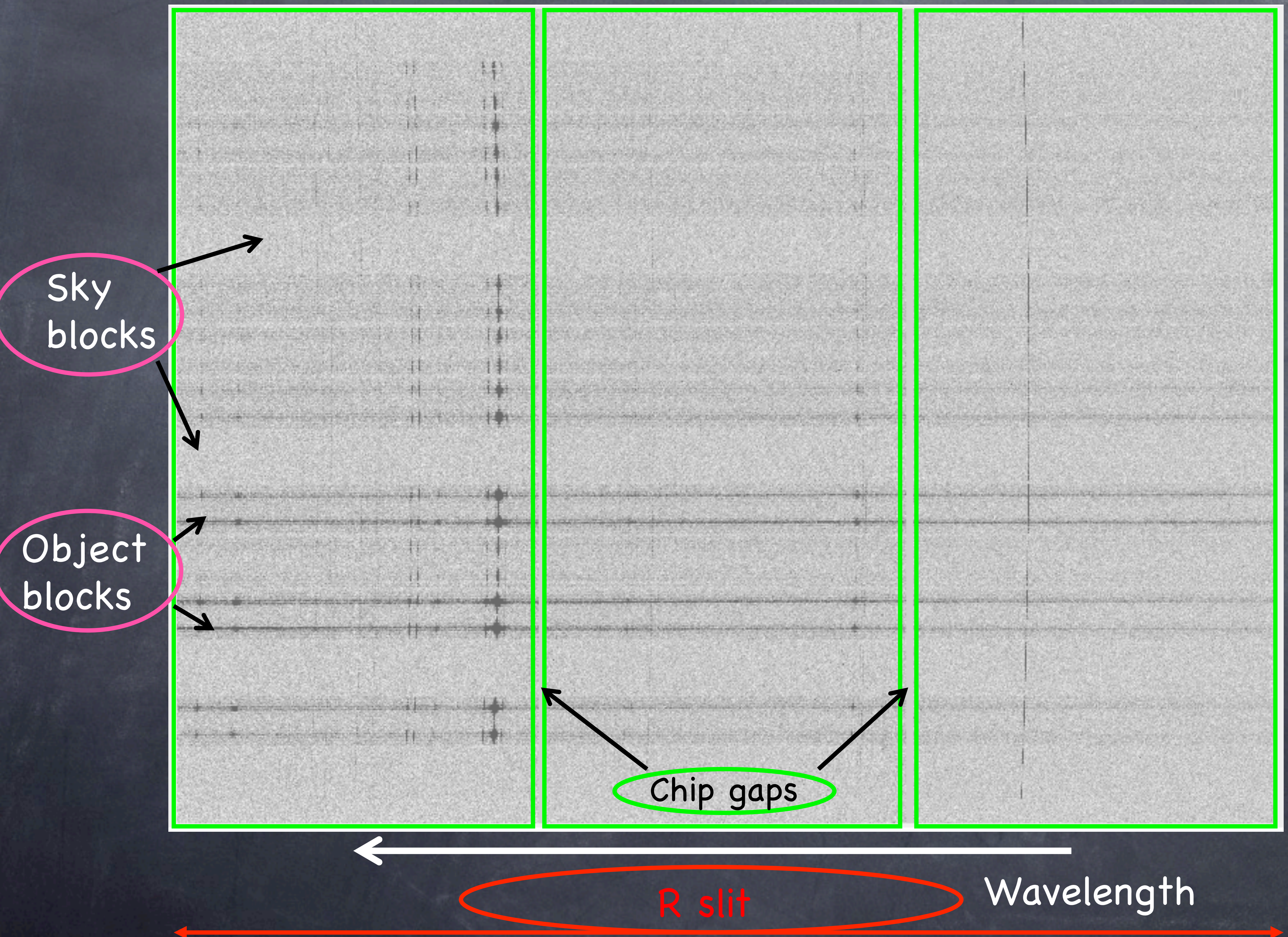
- Optical Integral Field Spectrograph
- Lenslet-fiber based design
- Various spectral capabilities
- Two spatial setting
  - "Two slit" mode:
    - 5"x7" (5"x3.5" sky)
    - 3,000 spectral pixels
    - 1500 spectra (500 sky)
  - "One slit" mode:
    - 5"x3.5" (5"x1.75" sky)
    - 6000 spectral pixels
    - 750 spectra (250 sky)
  - Spatial sampling of ~0.2" per fiber
- Dedicated sky fibers 60" offset for simultaneous sky



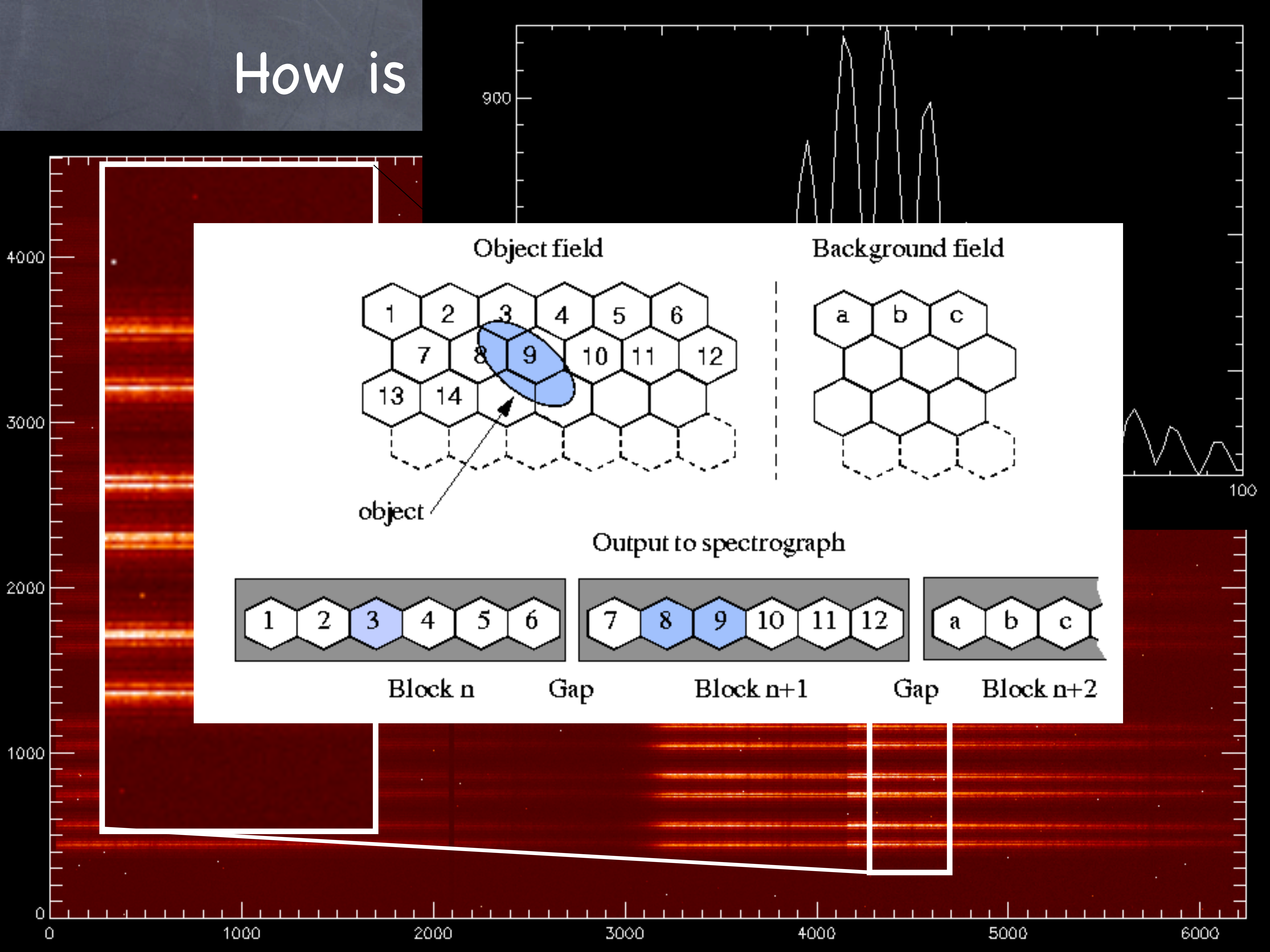
GMOS Example 2 slit mode M32



GMOS Example: 1 slit mode Mrk996



How is


900
4000
3000
2000
1000
0
0
1000
2000
3000
4000
5000
6000
100
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
1
2
3
4
5
6
7
8
9
10
11
12
a
b
c
Block n
Gap
Block n+1
Gap
Block n+2

GMOS IFU: Mask Definition Files

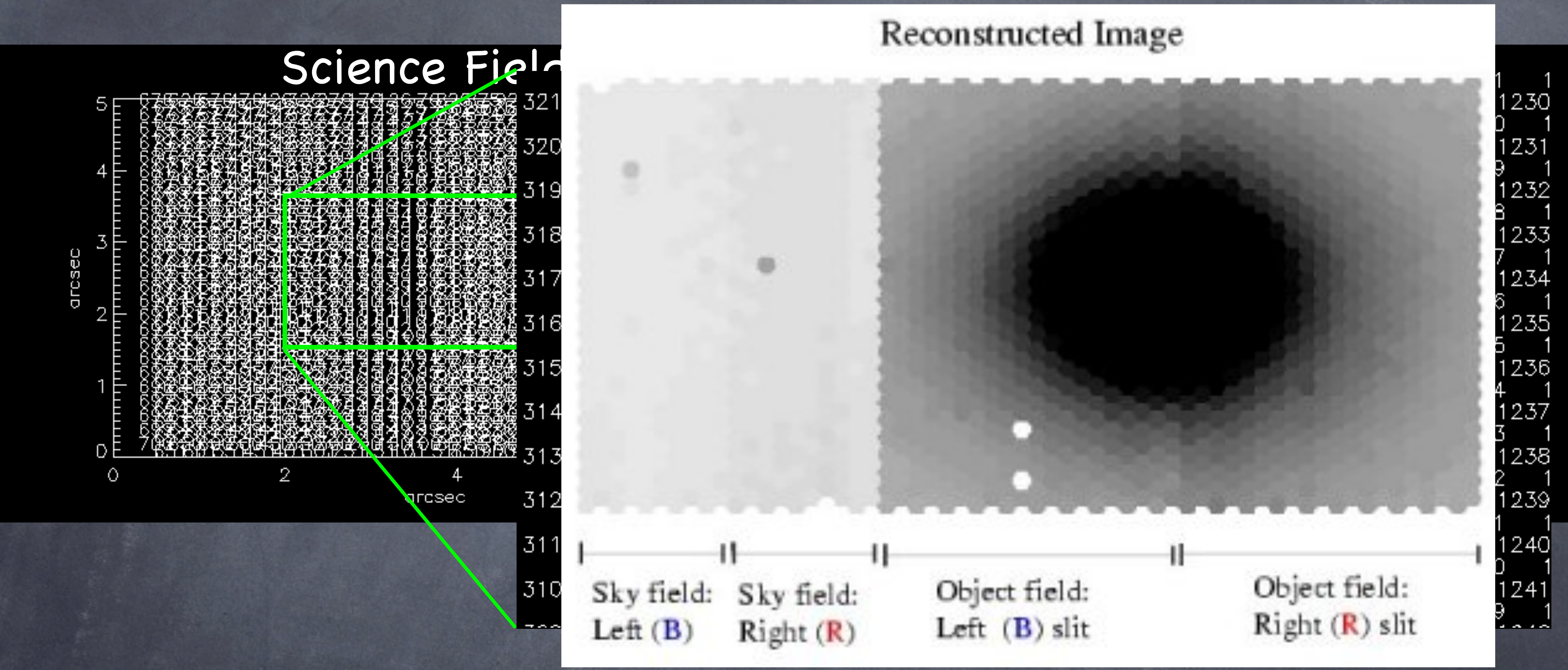
- Mask Definition File (MDF) provides sky coordinates of each fibre on CCD
- Together with wavelength calibration, provide translation from CCD (X,Y) to data-cube (RA, DEC, λ)

Slit mode	GMOS-N	GMOS-S
2 Slit	gnifu_slits_mdf.fits	gsifu_slits_mdf.fits
1 slit mode (Blue)	gnifu_slitb_mdf.fits	gsifu_slitb_mdf.fits
1 slit mode (Red)	gnifu_slitr_mdf.fits	gsifu_slitr_mdf.fits
N & S 2 Slit mode		gsifu_ns_slits_mdf.fits
N & S 1 slit mode (Blue)		gsifu_ns_slitb_mdf.fits
N & S 1 slit mode (Red)		gsifu_ns_ slitr_mdf.fits

gnifu_slits_mdf.fits

Column	1	2	3	4	5	6	7
Label	_NO_	_XINST_	_YINST_	BLOCK	BEAM	XLDIS	YLDIS
1	1	62.252	0.000	I_1	-1	1	16
2	2	62.252	0.200	I_2	1	3	16
3	3	62.252	0.400	I_3	1	5	16
4	4	62.252	0.600	I_4	1	7	16
5	5	62.252	0.800	I_5	1	9	16
6	6	62.252	1.000	I_6	1	11	16
7	7	62.252	1.200	I_7	1	13	16
8	8	62.252	1.400	I_8	1	15	16
9	9	62.252	1.600	I_9	1	17	16
10	10	62.252	1.800	I_10	1	19	16
11	11	62.252	2.000	I_11	1	21	16
12	12	62.252	2.200	I_12	1	23	16
13	13	62.252	2.400	I_13	1	25	16
14	14	62.252	2.600	I_14	1	27	16
15	15	62.252	2.800	I_15	1	29	16
16	16	62.252	3.000	I_16	1	31	16
17	17	62.252	3.200	I_17	1	33	16
18	18	62.252	3.400	I_18	1	35	16
19	19	62.252	3.600	I_19	1	37	16
20	20	62.252	3.800	I_20	1	39	16
21	21	62.252	4.000	I_21	1	41	16
22	22	62.252	4.200	I_22	1	43	16
23	23	62.252	4.400	I_23	1	45	16
24	24	62.252	4.600	I_24	1	47	16
25	25	62.252	4.800	I_25	1	49	16
26	26	62.078	4.900	I_26	1	50	17
27	27	62.078	4.700	I_27	1	48	17
28	28	62.078	4.500	I_28	1	46	17
29	29	62.078	4.300	I_29	1	44	17
30	30	62.078	4.100	I_30	1	42	17
31	31	62.078	3.900	I_31	1	40	17
32	32	62.078	3.700	I_32	1	38	17
33	33	62.078	3.500	I_33	1	36	17
34	34	62.078	3.300	I_34	1	34	17
35	35	62.078	3.100	I_35	1	32	17
36	36	62.078	2.900	I_36	1	30	17

GMOS IFU: Mask Definition Files



- 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 Reduction

Organizing your files: suggestion

Raw data:

calibrations/ - all baseline daytime calibration raw images

science/ - all science data

standards/ - photometric standard stars (nighttime calibrations)

Reductions:

reductions/ - all reductions

└ calibrations/ - reductions of daytime calibrations

└ Obj1/ - reduction of the first science object

  └ Grating1/ - first grating

    Grating2/ - second grating

  └ combined/ - combined images

  Obj2/ - reduction of the second science object

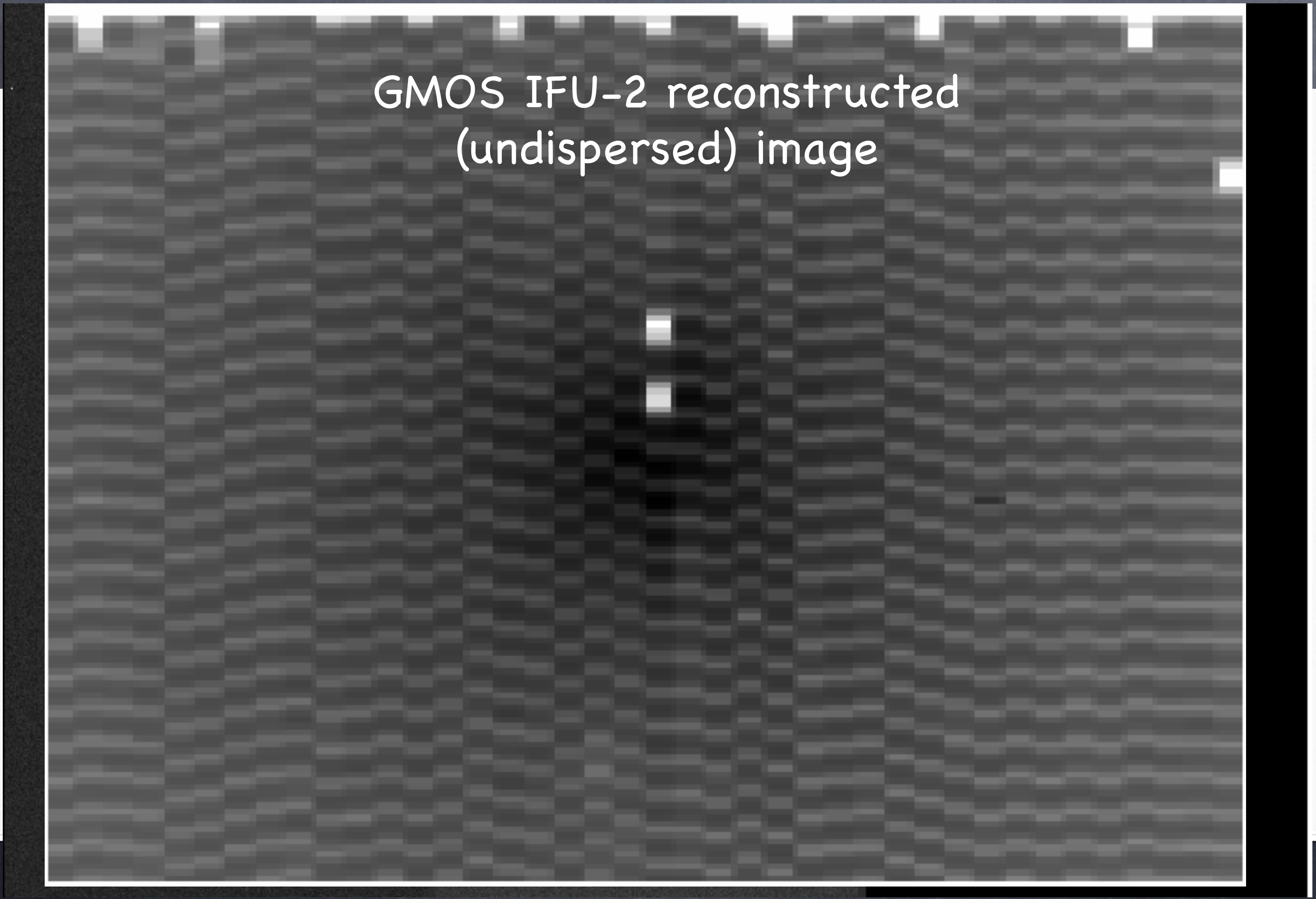
└ fluxstandard/ - flux calibration

GMOS IFU Reduction

Typical GMOS IFU observations

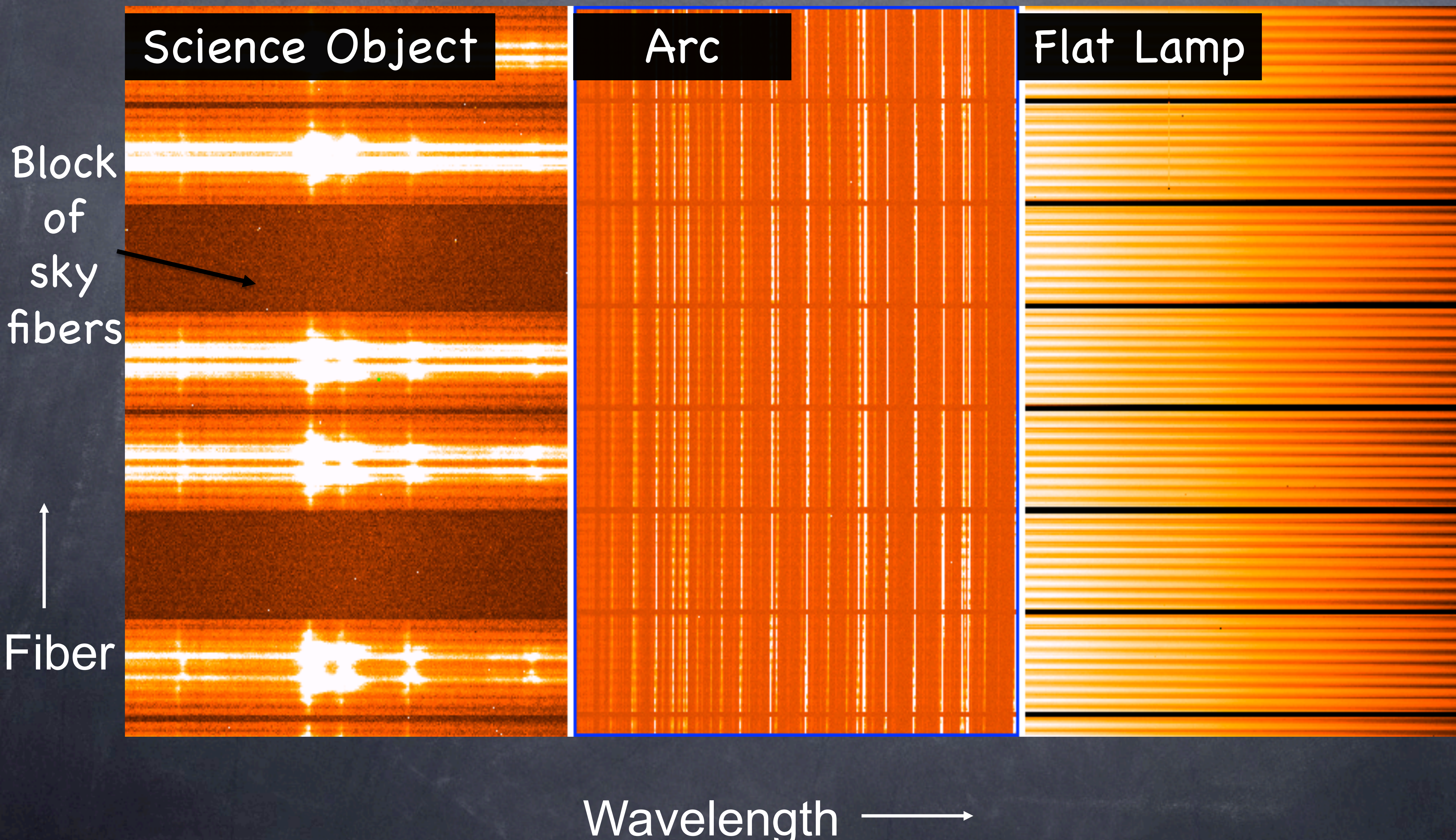
- Science Observations
  - Acquisition
    - Direct image of the field → initial offsets
    - Un-dispersed IFU image → fine centering
  - Observation sequence:
    - Flat (fringing is flexure-dependent)
    - Science Exposure (up to 1 hour)
    - Flat (and CuAr arc if you need good Wavev. Calib.)
- Daytime calibrations (Baseline)
- Bias - GN(GS)-CALYYYYMMDD
  - Twilight sky flat and CuAr arcs (inside the program)
- Nighttime calibrations (Baseline) - GN(GS)-CALYYYYMMDD
  - Flux standard for relative flux calibration (not – coincident)

GMOS IFU Reduction -> acquisition



GMOS IFU Reduction

Typical GMOS IFU raw data



GMOS IFU Reduction

- Basic IRAF data reduction information in the web.
- Good starting point to reduce your **data and form the base of this tutorial**
- **Goal → to get a combined data cube with basic calibrations (wavelength, transmission, etc...)**
- Dataset
  - SV data on NGC 1068 from 2001
  - 2-slit mode IFU → 5"x7" per pointing
  - 2x2 mosaic for field coverage
  - B600 grating, targeting H_{α} and continuum
  - Bias is prepared already
  - Twilight sky included
  - Flux standard also included (not described here)

GMOS IFU Reduction

Step to follow

① Bias and over-scan subtraction from all images (science spectra, flats, twilight sky, CuAr arcs, etc) - recommended

② Identify the fibers using a flat image

③ Construct the Flat

I. Spectral flat field to correct for transmission function → using the GCAL flats

II. Spatial flat field to correct for illumination function & fiber response → using twilight sky

④ Establish wavelength solution using CuAr arcs

⑤ Reducing science images

⑥ Construct Data Cubes

Step 1: bias subtraction

- Use gprepare on your data (Science, flats, CuAr arcs). The task will add the MDF to the frames
  - Suggestion → copy the MDF file to your local directory in case that you need to edit it → gnifu_slits_mdf.fits

```
gprepare @obj.lst rawpath=rawdir$ fl_addmdf+\
mdffile="gnifu_slits_mdf.fits" mdfdir="gmos$data/"
```

- Use gfreduce for bias and over scan subtraction
  - Suggestion: do this interactively

```
gfreduce g//@obj.lst fl_addmdf- fl_inter+ \
fl_over+ fl_extract- fl_gsappwave- fl_wavtran- \
fl_skysub- fl_fluxcal- fl_gscrrej- slits=both
```

Step 2: identifying the fibers (spectra)

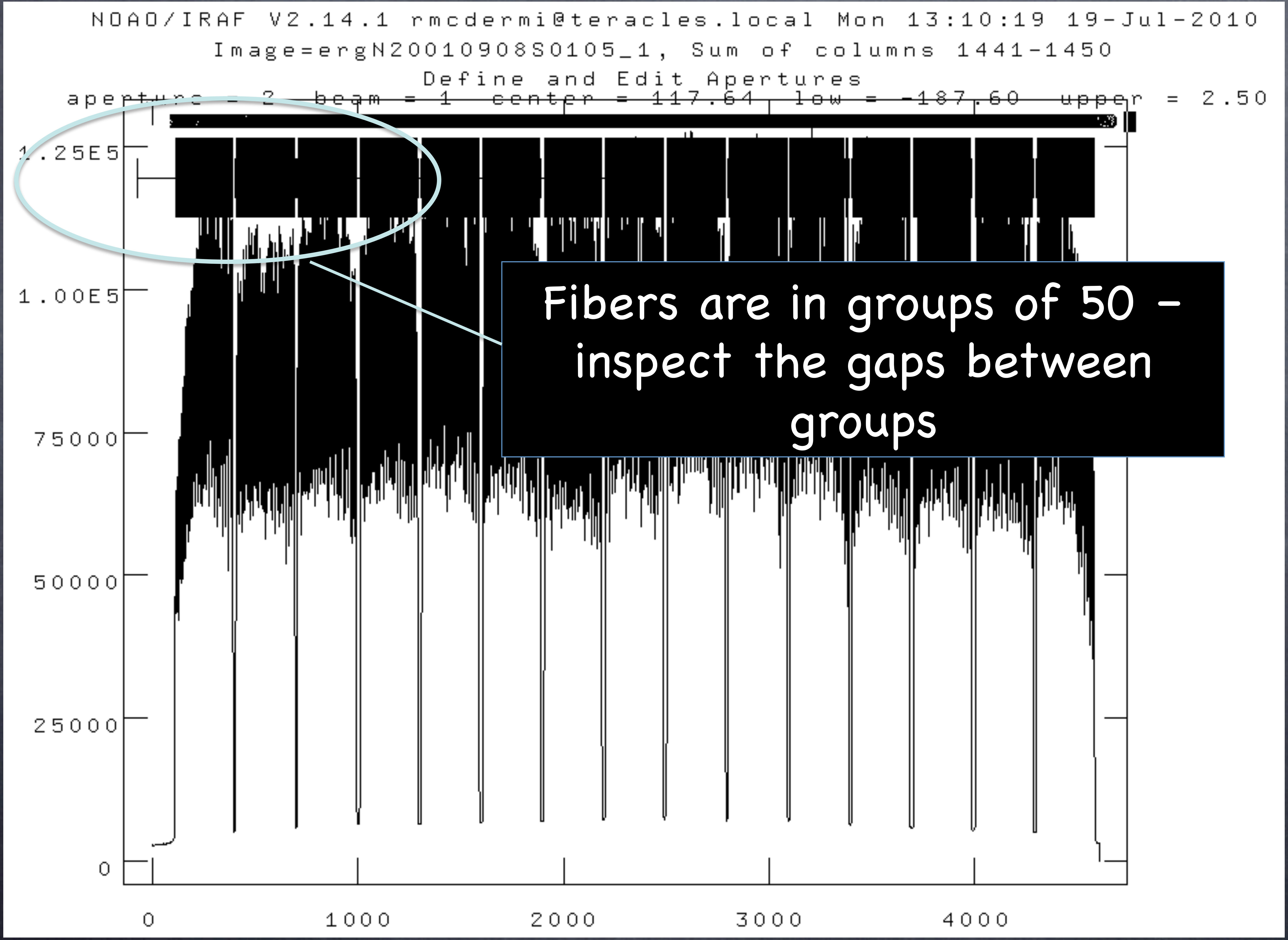
- CRUCIAL ste … an be traced on the detector.
- Use the flat … bers on the detector, and …
- Once again, … ely
  - We want … s only
  - There are … s-identification

```
gfreduce rg… df- fl_trim- \
fl_bias- fl… l_gscrrej- \
fl_fluxcal-…
```

Column	1	2	3	4	5	6	7
Label	_NO_	_XINST_	_YINST_	BLOCK	BEAM	XLDIS	YLDIS
1	1	62.252	0.000	I_1	-1	1	16
2	2	62.252	0.200	I_2	1	3	16
3	3	62.252	0.400	I_3	1	5	16
4	4	62.252	0.600	I_4	1	7	16
5	5	62.252	0.800	I_5	1	9	16
6	6	62.252	1.000	I_6	1	11	16
7	7	62.252	1.200	I_7	1	13	16
8	8	62.252	1.400	I_8	1	15	16
9	9	62.252	1.600	I_9	1	17	16
10	10	62.252	1.800	I_10	1	19	16
11	11	62.252	2.000	I_11	1	21	16
12	12	62.252	2.200	I_12	1	23	16
13	13	62.252	2.400	I_13	1	25	16
14	14	62.252	2.600	I_14	1	27	16
15	15	62.252	2.800	I_15	1	29	16
16	16	62.252	3.000	I_16	1	31	16
17	17	62.252	3.200	I_17	1	33	16
18	18	62.252	3.400	I_18	1	35	16
19	19	62.252	3.600	I_19	1	37	16
20	20	62.252	3.800	I_20	1	39	16
21	21	62.252	4.000	I_21	1	41	16
22	22	62.252	4.200	I_22	1	43	16
23	23	62.252	4.400	I_23	1	45	16
24	24	62.252	4.600	I_24	1	47	16
25	25	62.252	4.800	I_25	1	49	16
26	26	62.078	4.900	I_26	1	50	17
27	27	62.078	4.700	I_27	1	48	17
28	28	62.078	4.500	I_28	1	46	17
29	29	62.078	4.300	I_29	1	44	17
30	30	62.078	4.100	I_30	1	42	17
31	31	62.078	3.900	I_31	1	40	17
32	32	62.078	3.700	I_32	1	38	17
33	33	62.078	3.500	I_33	1	36	17
34	34	62.078	3.300	I_34	1	34	17
35	35	62.078	3.100	I_35	1	32	17
36	36	62.078	2.900	I_36	1	30	17

Dead fiber

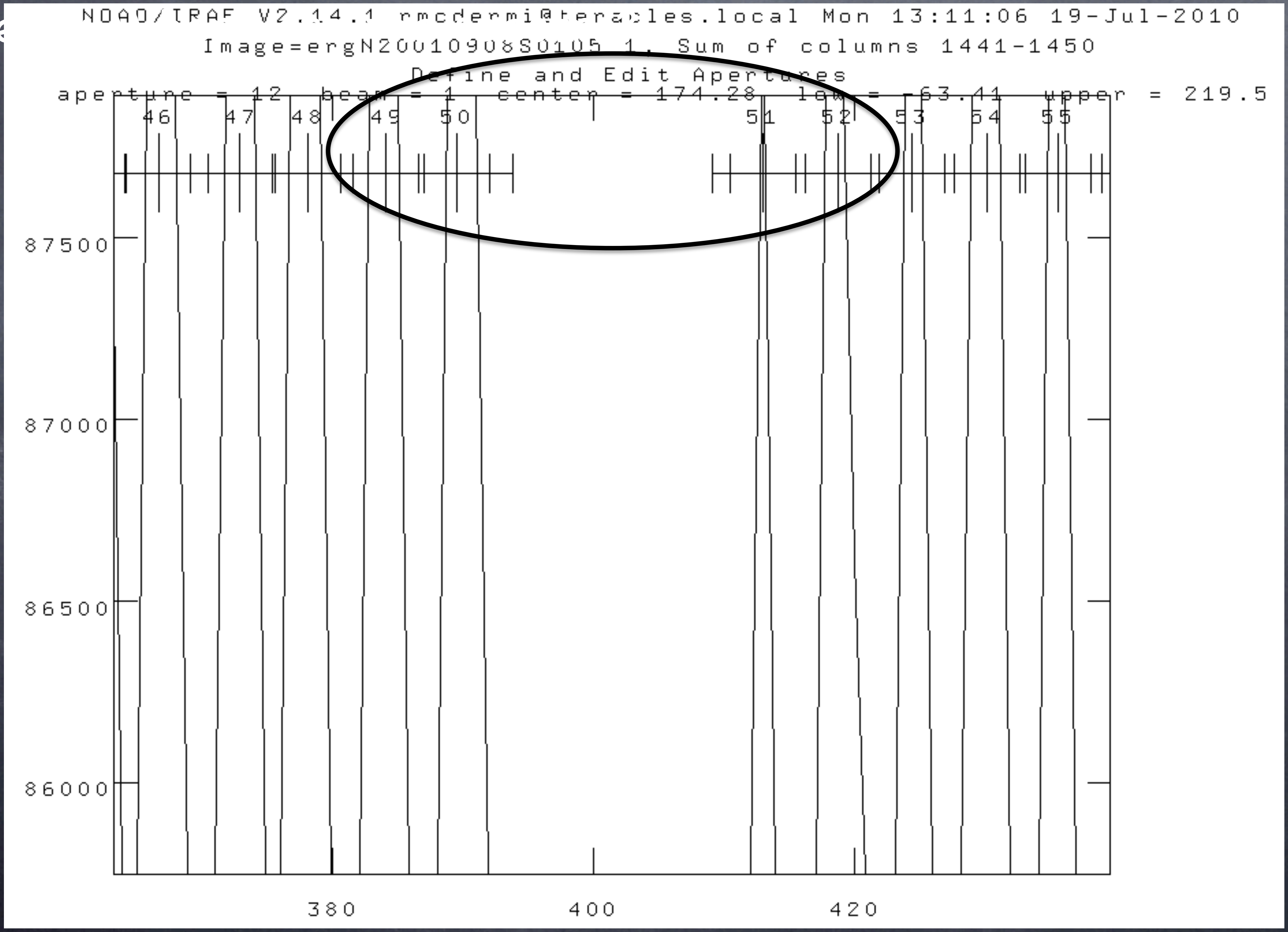
Step 2: identifying the fibers (spectra)



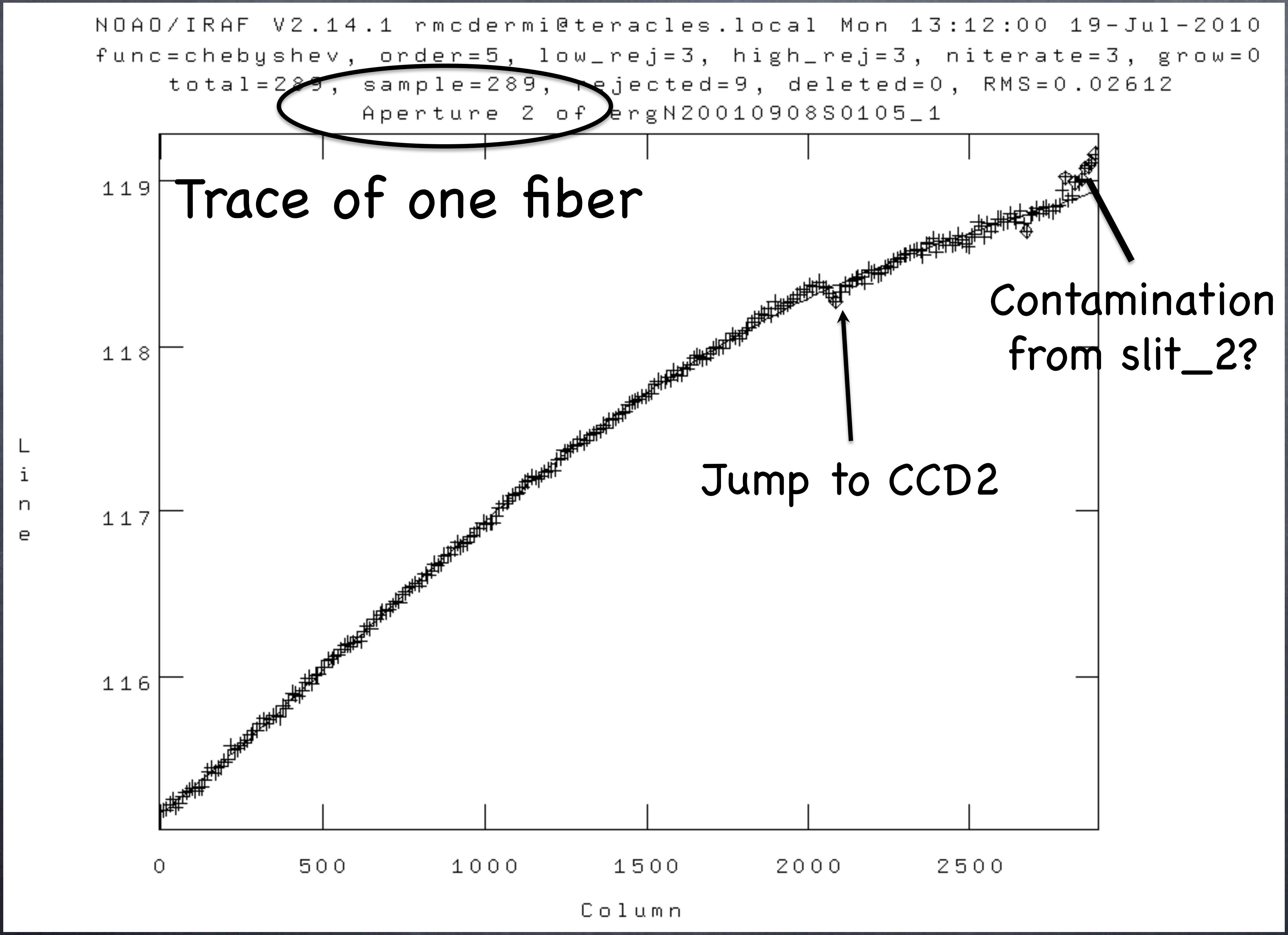
Fibers are in groups of 50 – inspect the gaps between groups

Step 2: identifying the fibers (spectra)

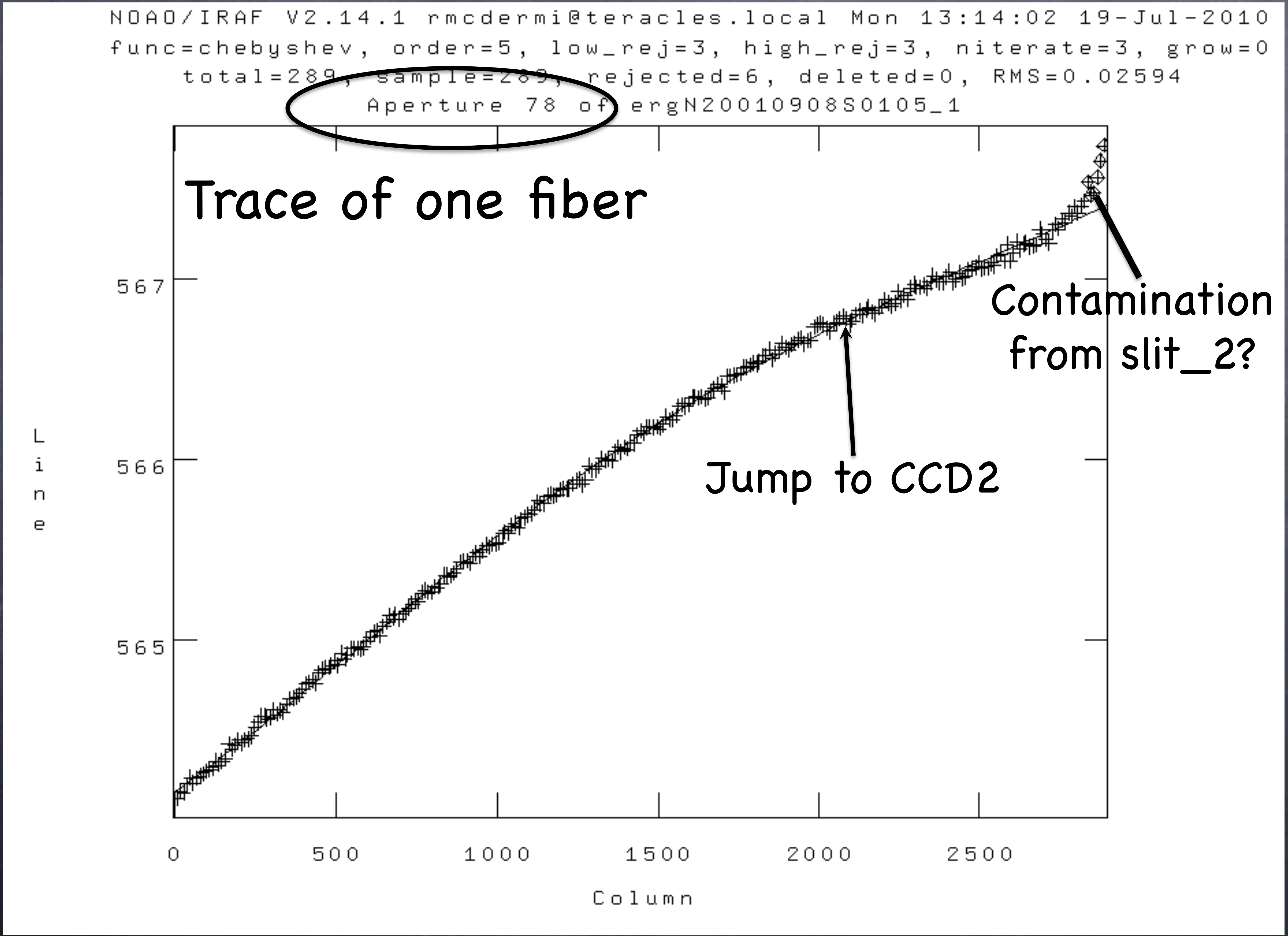
Ste



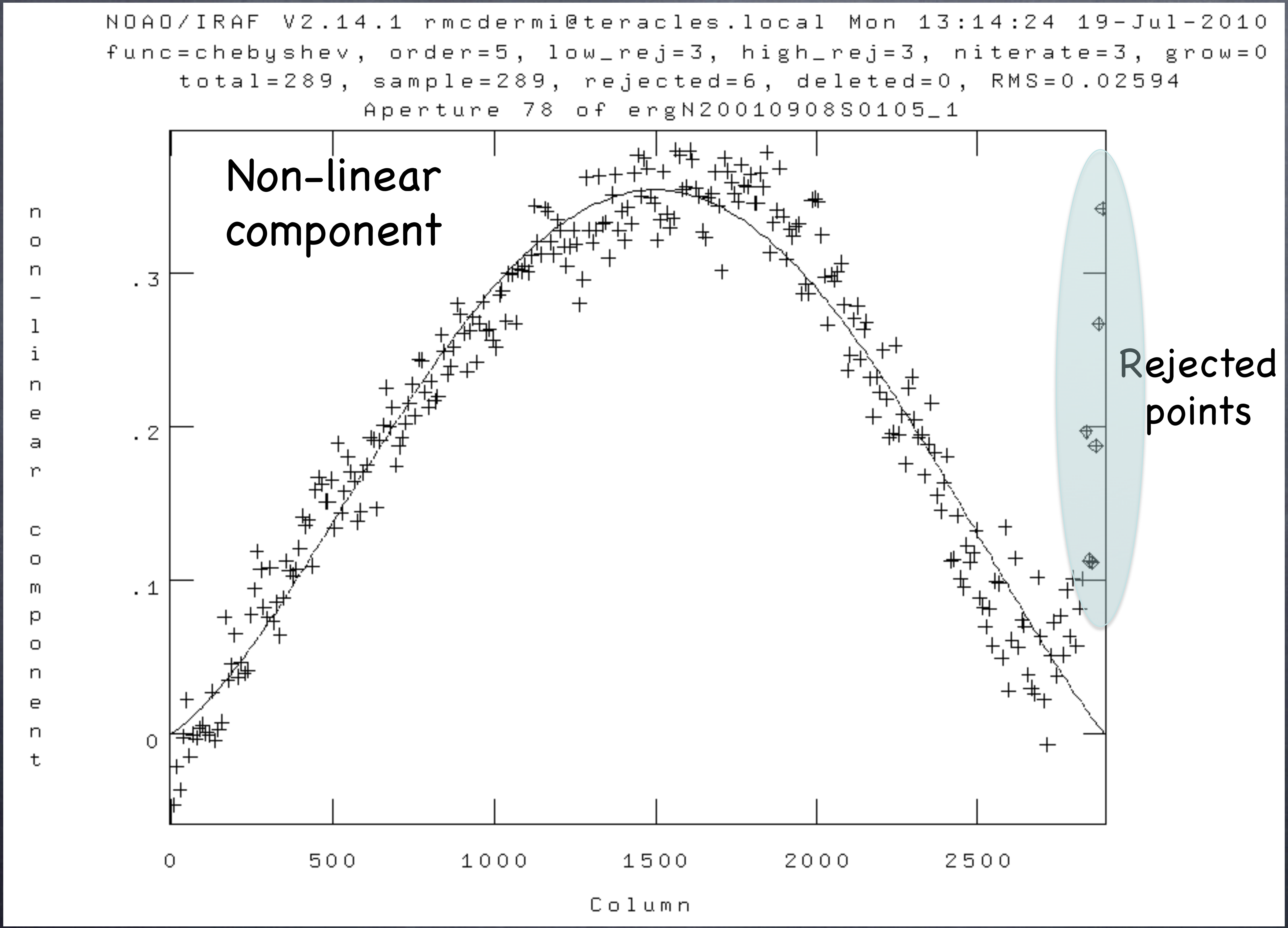
Step 2: identifying the fibers (spectra)



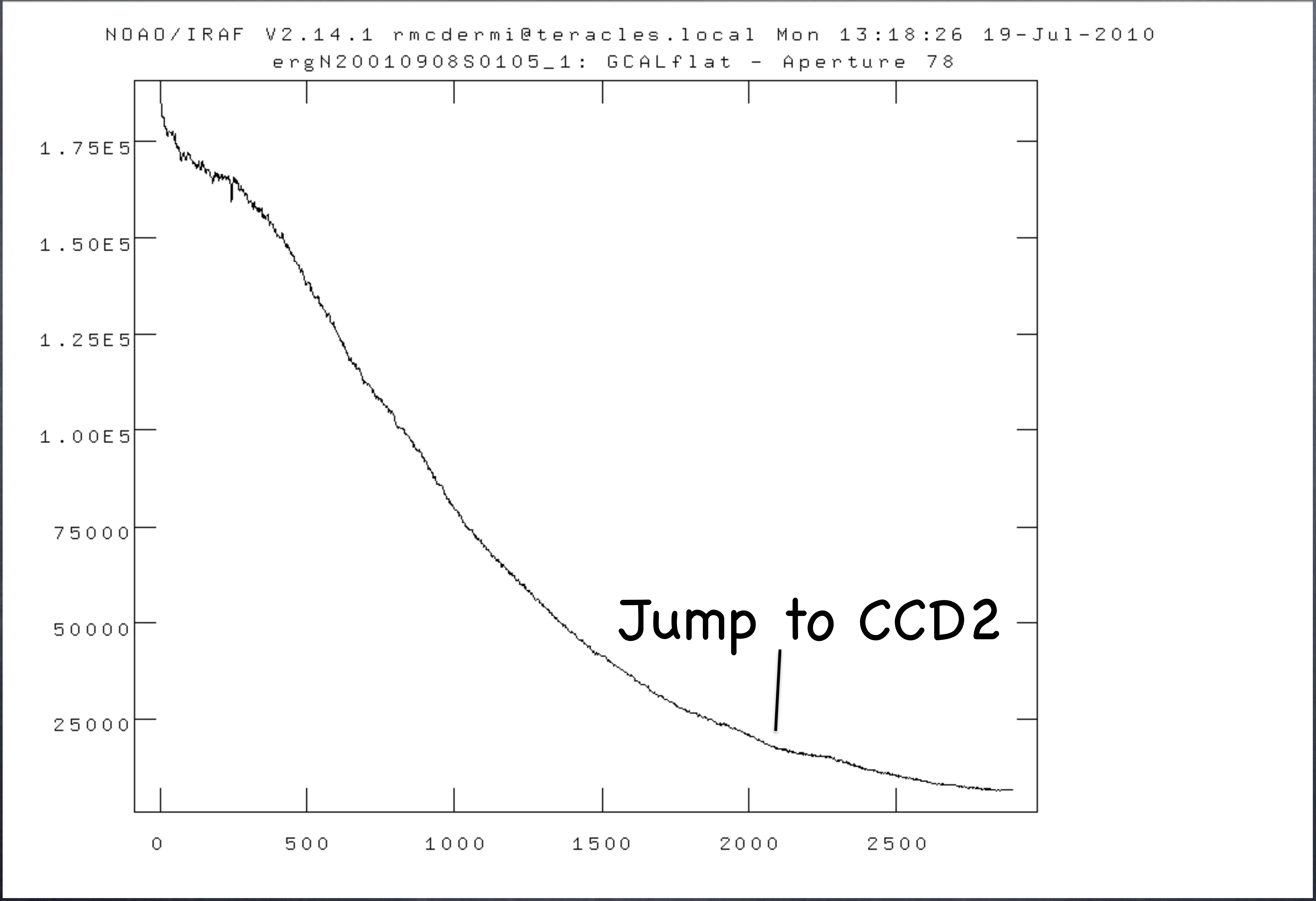
Step 2: identifying the fibers (spectra)



Step 2: identifying the fibers (spectra)

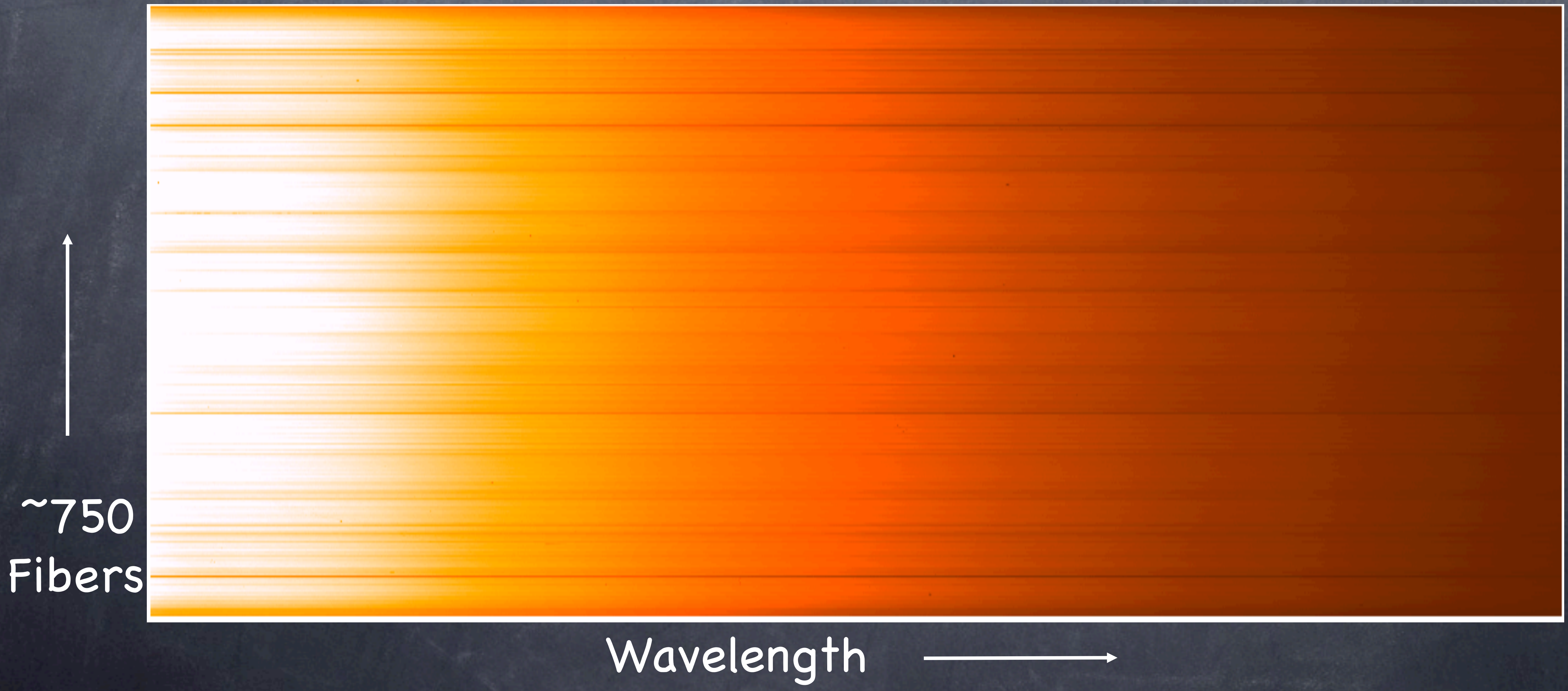


Step 2: identifying the fibers (spectra)



Step 2: identifying the fibers (spectra)

- Following extraction, data are stored as 2D images in one MEF (one image per slit) → ergN20010908S0105
- This format is VERY useful for inspecting the datacube



Step 3: prepare the flat-field

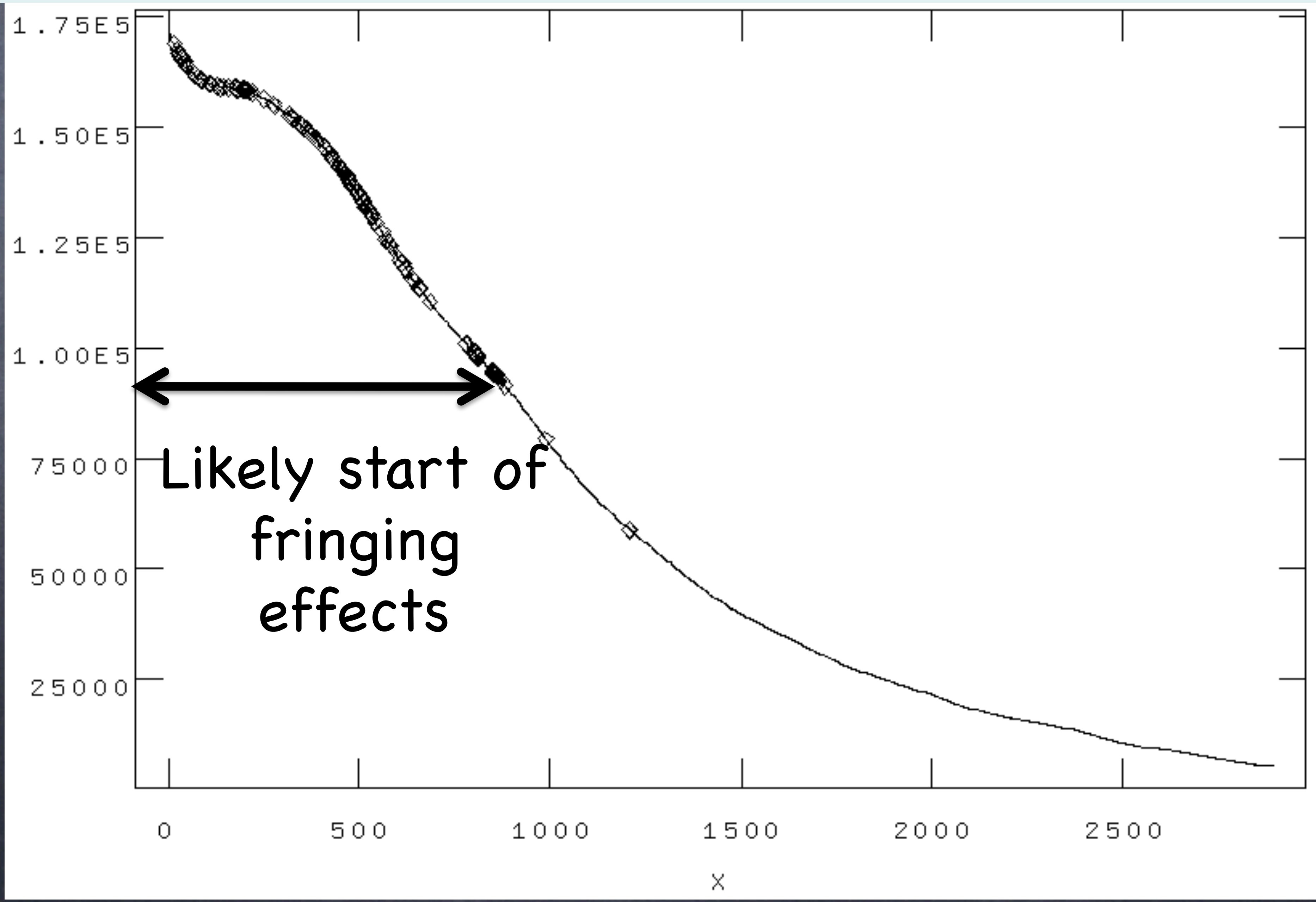
- Flat-fielding has two components:
  - Spectral Flat-field
    - ➢ Correct for instrument spectral transmission response
    - ➢ Use black body lamp and divide by fitted smooth function
  - Spatial Flat-field:
    - ➢ Correct for illumination function & fiber response
    - ➢ Use Twilight sky flat to renormalize the (fit-removed) flat lamp
- But first, we have to trace the fibers for twilight sky flat using the processed flat image as reference to trace the fibers → gfreduce looks in the "database/"

```
gfreduce rgN20010908S0112 fl_bias- fl_over- fl_gscrrej- \
fl_wavtran- fl_skysub- fl_inter+ slits=both trace-
recenter+ ref="ergN20010908S0105"
```

Step 3: prepare the flat-field

- Make response curves with twilight correction

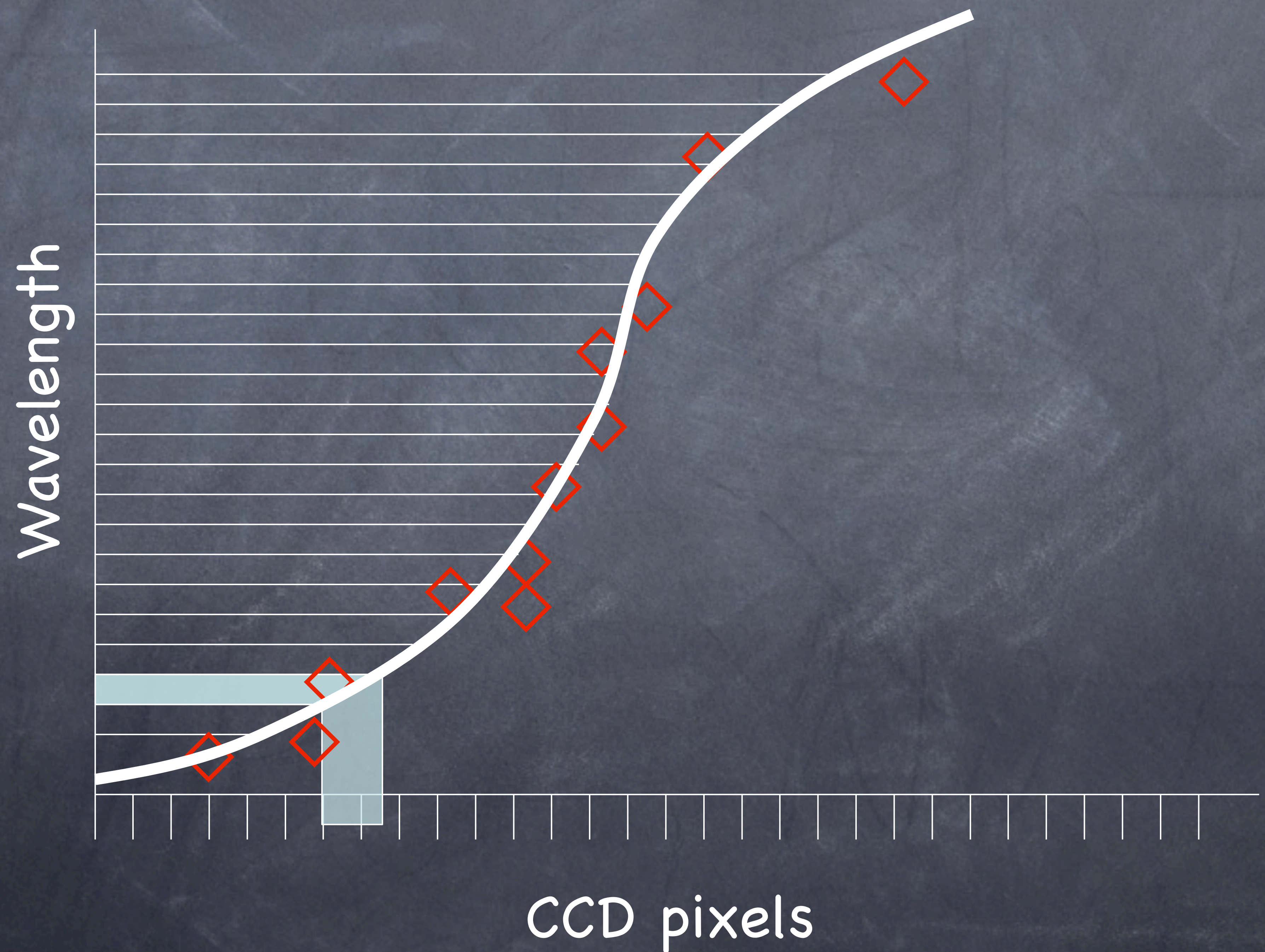
```
gfresponse ergN20010908S0105 ergN20010908S0105_resp112
sky=ergN20010908S0112 order=95 fl_inter+ func=spline3
sample="*"
```



Final flat

Step 4: wavelength calibration

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



Step 4: wavelength calibration

- Note that the arc in the tutorial has not been observed in the science sequence.
- CuAr arcs - over-subtract instead of using the bias since the bias does not apply to fast read and low gain
- Using the flat to trace the fibers.

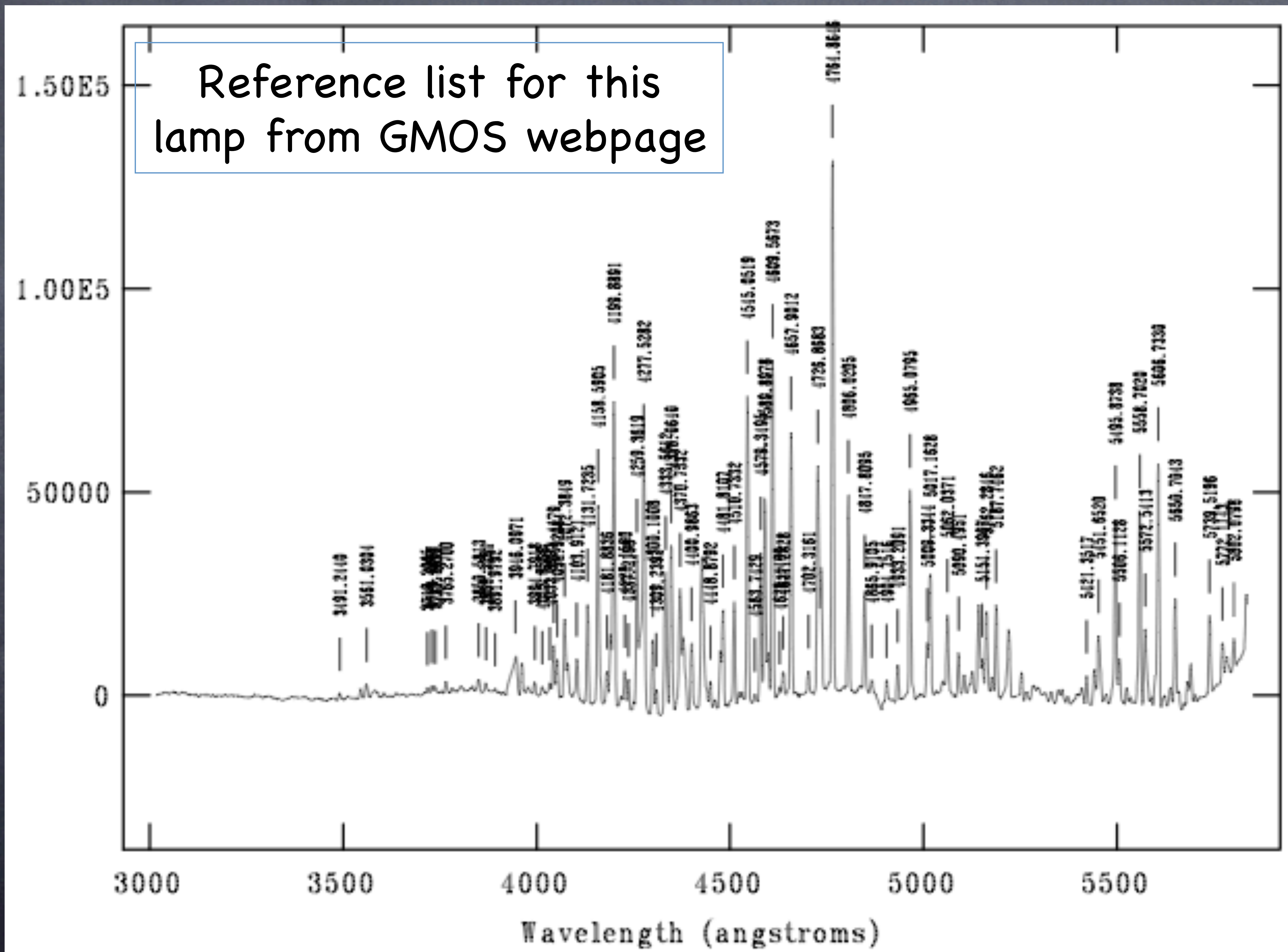
```
gfreduce N20010908S0108.fits fl_wavtran- fl_inter+
ref=ergN20010908S0105 recenter- trace- fl_skysub-
fl_gscrrej- fl_bias- fl_over+ order=1 weights=none
biasrows
```

- Establishing wavelenght calibrtation

```
gswavelength ergN20010908S0108 fl_inter+ nlost=10
```

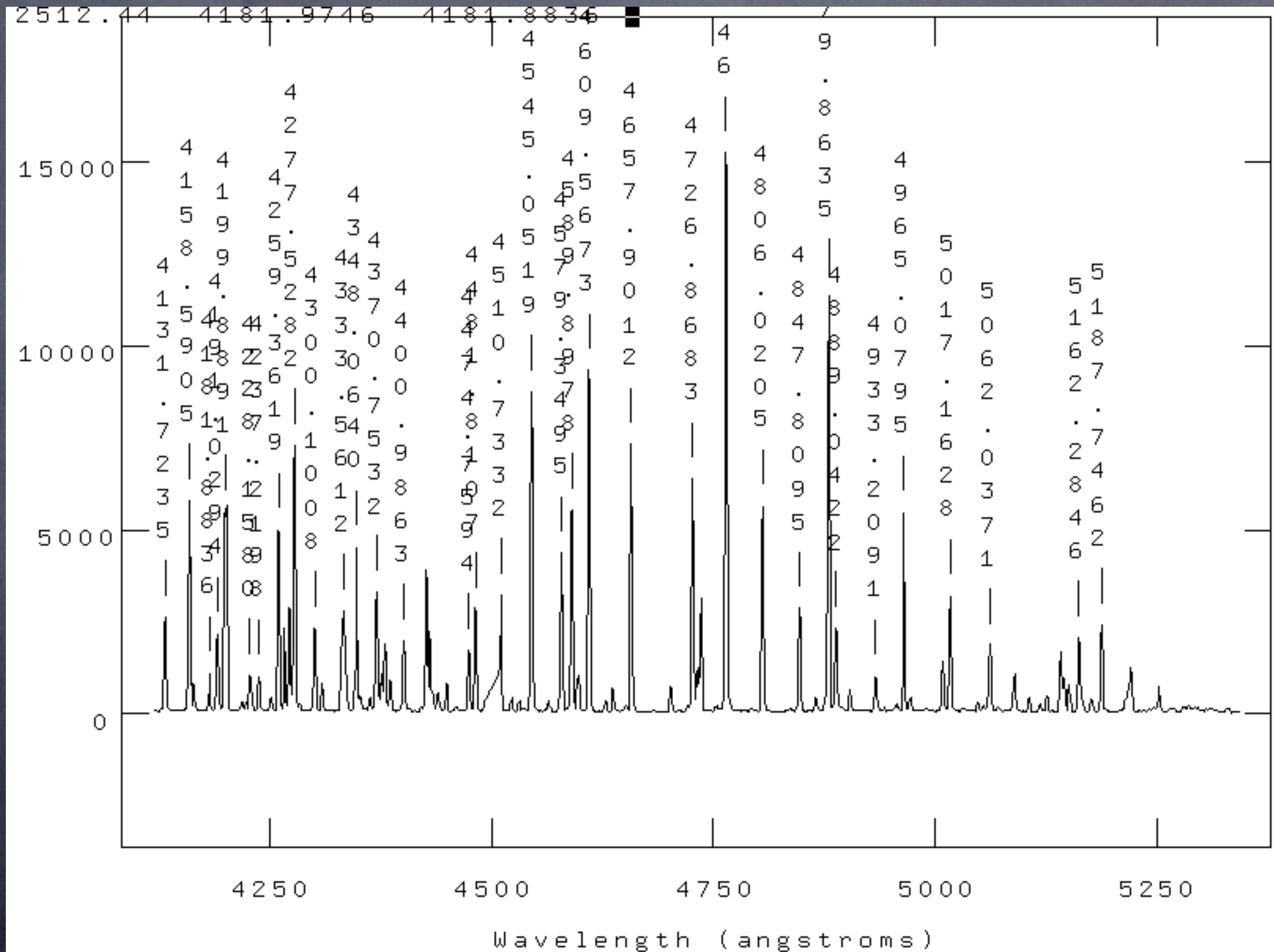
Step 4: wavelength calibration

First step: Identify lines in your arc frame

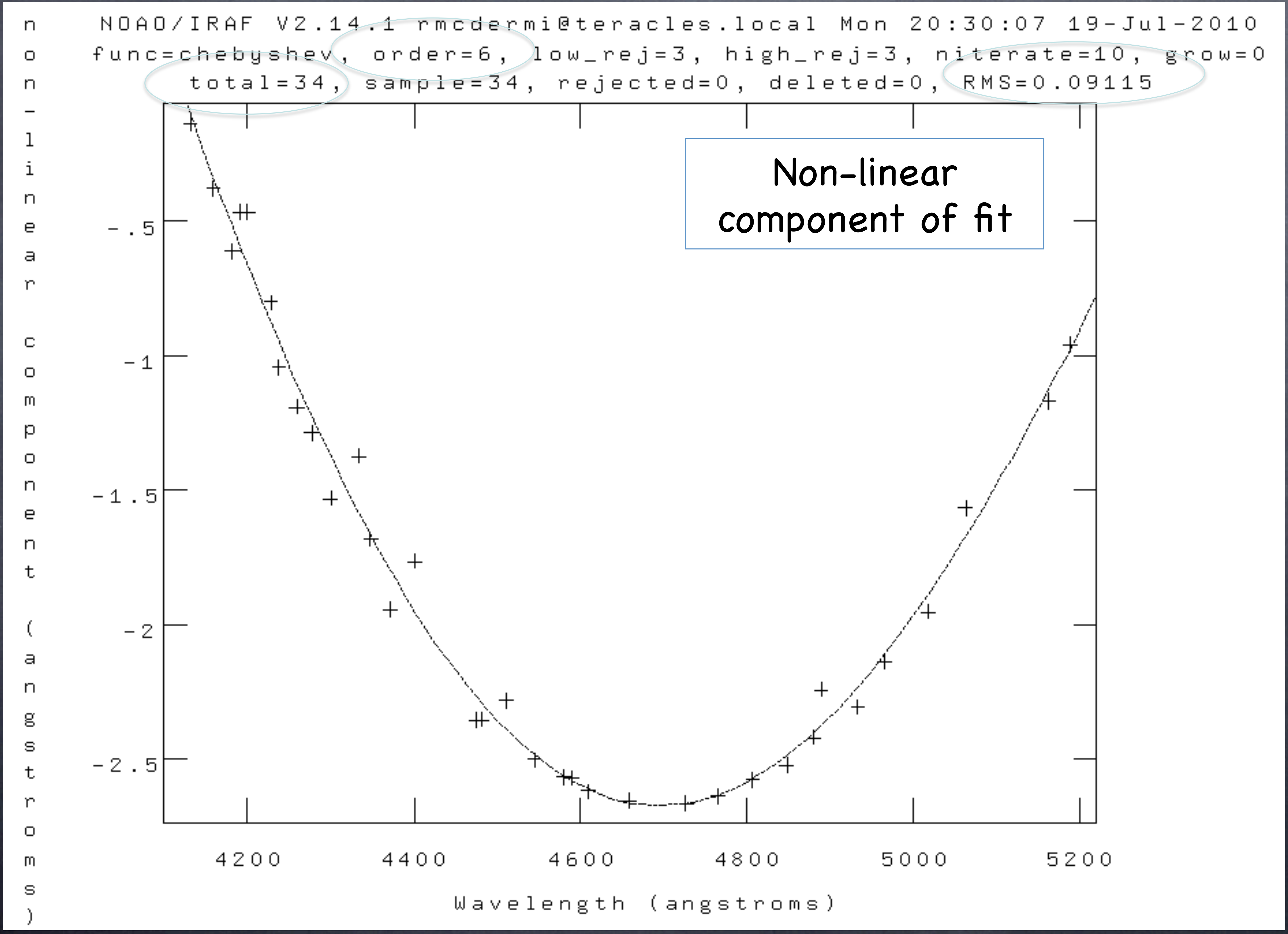


Step 4: wavelength calibration

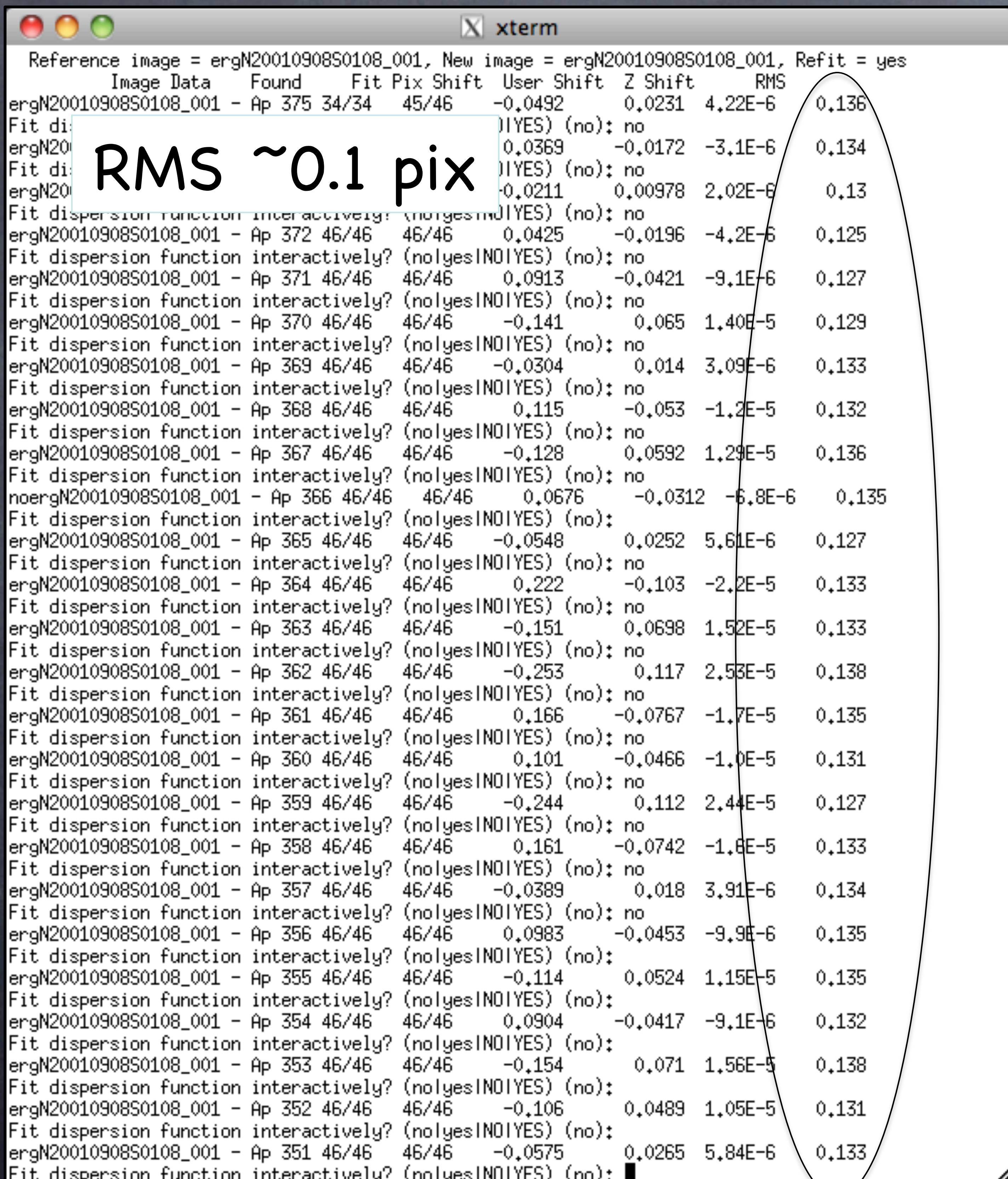
- Marked lines in GMOS spectrum, after some tweaking...



Step 4: wavelength calibration



Step 4: wavelength calibration

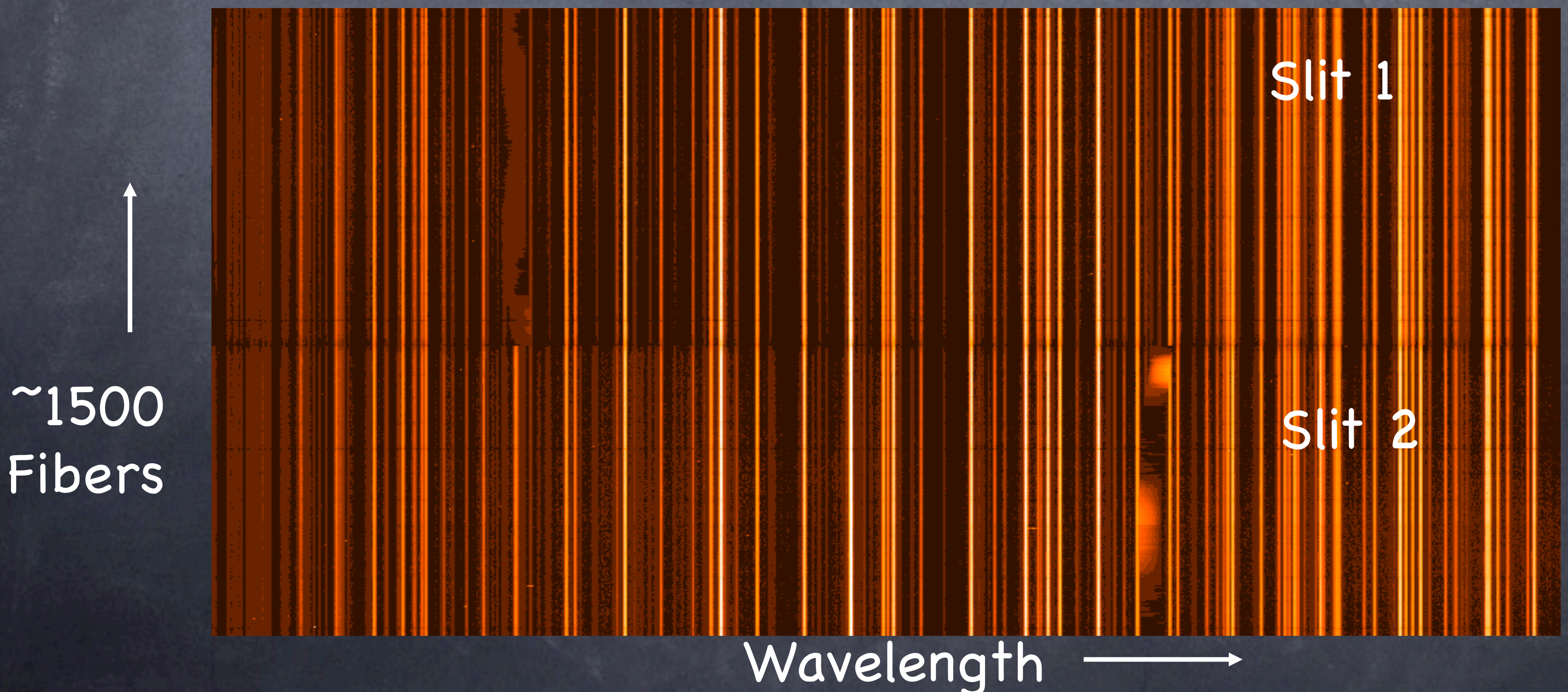


- First solution used as starting point for subsequent fibers
- Usually robust, but should be checked carefully.
- Often best to edit the reference line file (CuAr_GMOS.dat).
- Two slits are treated separately – need to repeat

Step 4: wavelength calibration

Checking the wavelength calibration

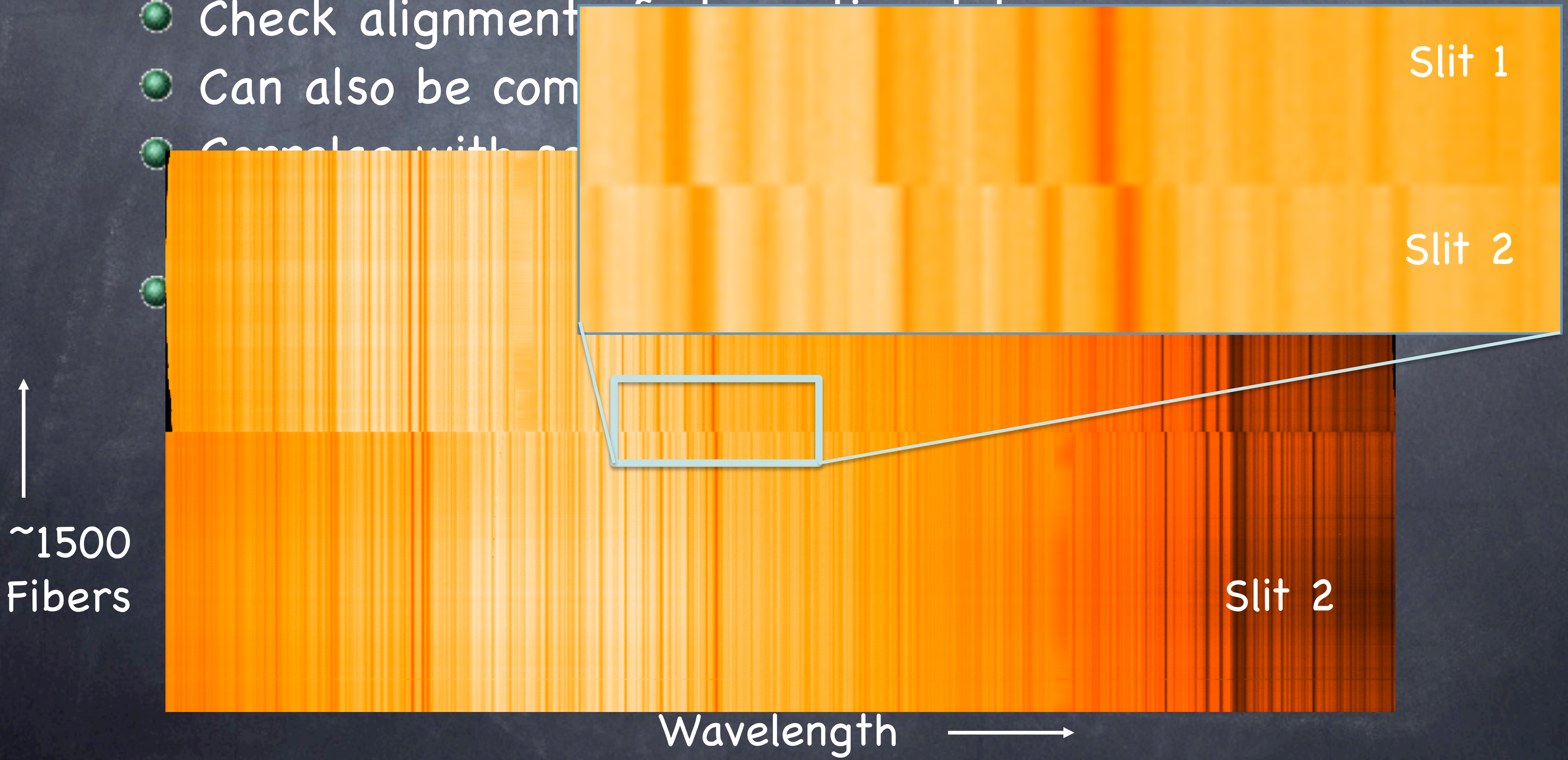
- Testing quality of wavelength calibration is critical
  - Not always obvious from your science data
  - May not have skylines.
  - Detect nonlinearity systematics
- Basic check is to apply the calibration solution to the arc itself, and inspect the 2D image



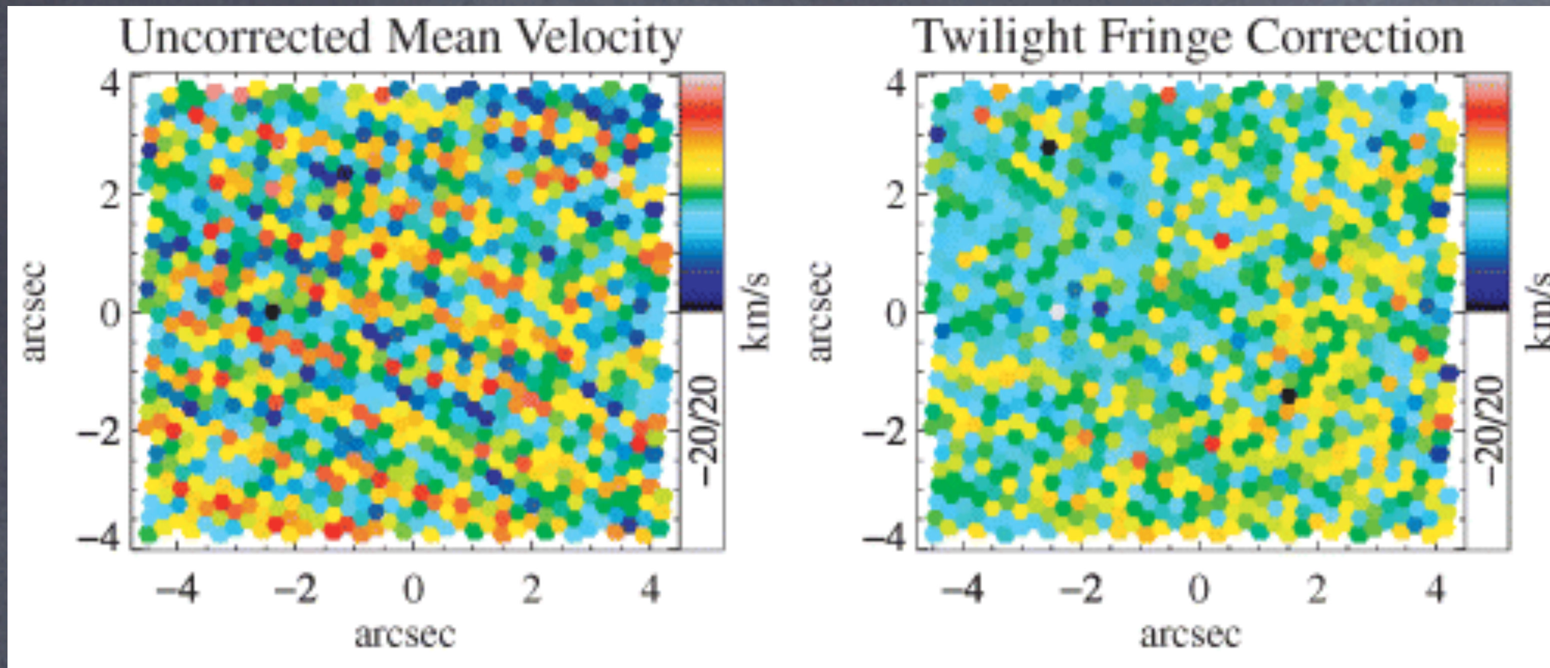
Step 4: wavelength calibration

Checking the wavelength calibration

- Twilight sky is also an excellent test
  - Reduce it like your science data
  - Check alignment
  - Can also be com

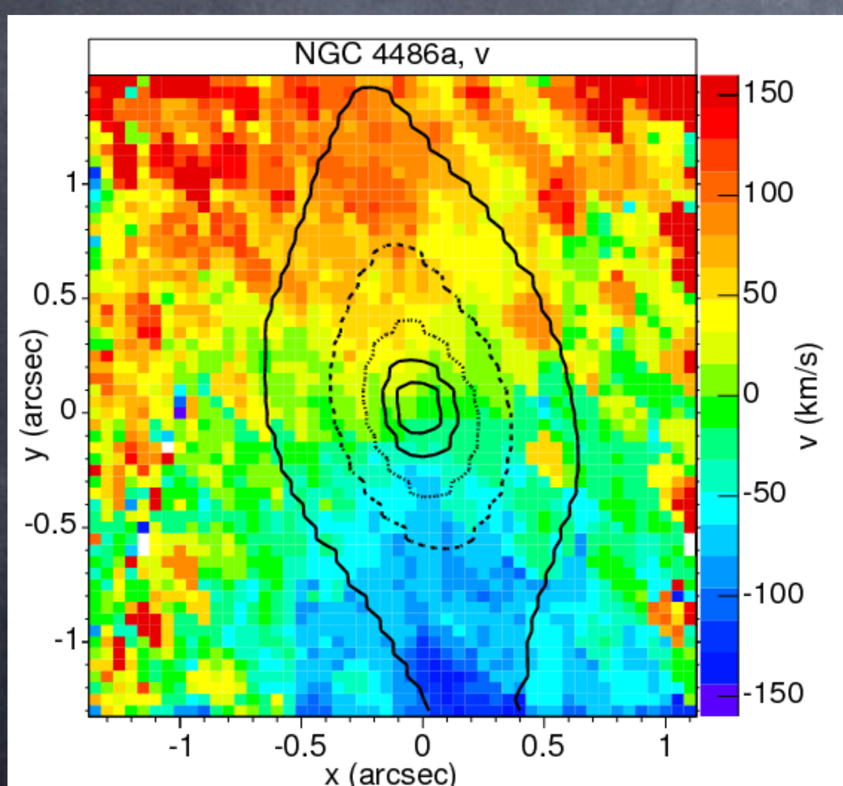


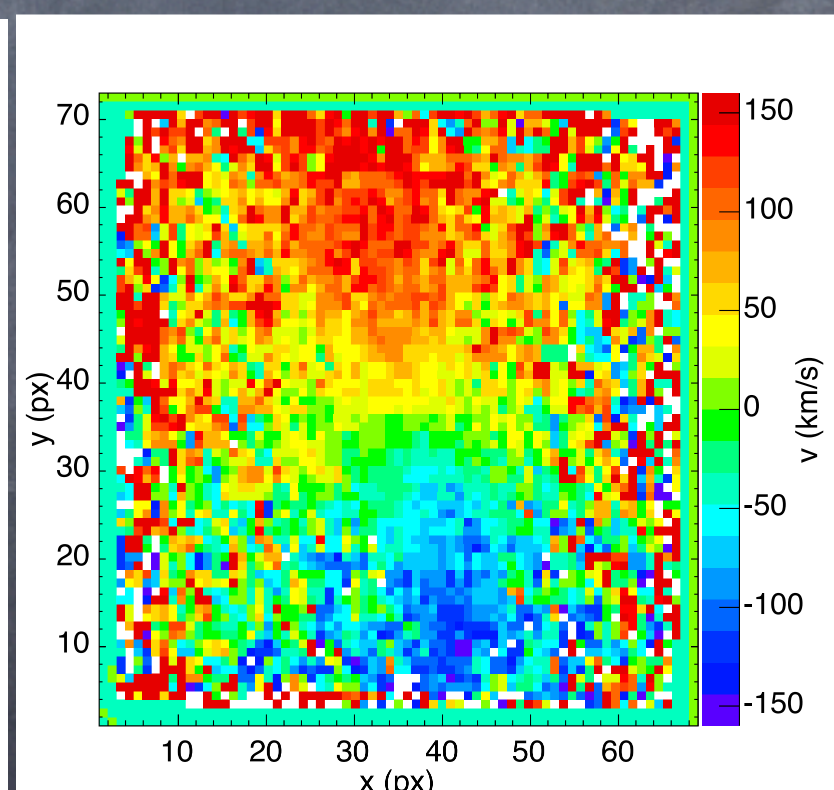
The effect of fringing from bad flat



OASIS

McDermid et al. 2006





SINFONI data on NGC 4486a

Nowak et al.

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

Step 5: reducing the science data

- Now run "gfreduce" on science data to (bias subtraction already done):
  - Extract traces using the flat as a reference
  - Apply flat-fielding correction (output from "gfresponse")
  - Cleaning cosmic rays using a Laplacia filter → Laplacian Cosmic Ray Identification routine by P. van Dokkum
  - Apply wavelength solution and rectify the spectra
  - Sky subtraction

```
gfreduce rgN20010908S0101 slits=both fl_inter-  fl_over-
fl_bias- fl_wavtran+ fl_flux- refer=ergN20010908S0105
recenter- trace- wavtran=ergN20010908S0108
response=ergN20010908S0105_resp112 slits=both
```

Step 6: Constructing Data Cube

Data cube is constructed with "gfcube" → Resample extracted IFU spectra onto an x-y-λ datacube

```
gfcube stergN20010908S0101 sample=0.1 fl_atmdisp+
```

- sample=0.1 → spatial sampling rate or pixel size to use in the output datacube.
- fl_atmdisp=yes → Compensate for atmospheric dispersion (differential refraction) when resampling the fibre spectra onto the output datacube
  - Differential atmospheric refraction (DAR) estimated using the atmospheric model from the version of SLALIB distributed with IRAF (v2.3.0 as of gemini v1.10) → "help refro"

Differential Atmospheric Refraction

- Lac … th
  GM
- Atn … velength
  - S
- Can … n λ
  plar
- Use … good.
  OR.
- Can … DAR IFU
  cor
  - h
    s … fraction