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Galaxy evolution in 3D and the pitfalls of reducing your GMOS IFU data



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University of Texas at Austin

Quick talk overview

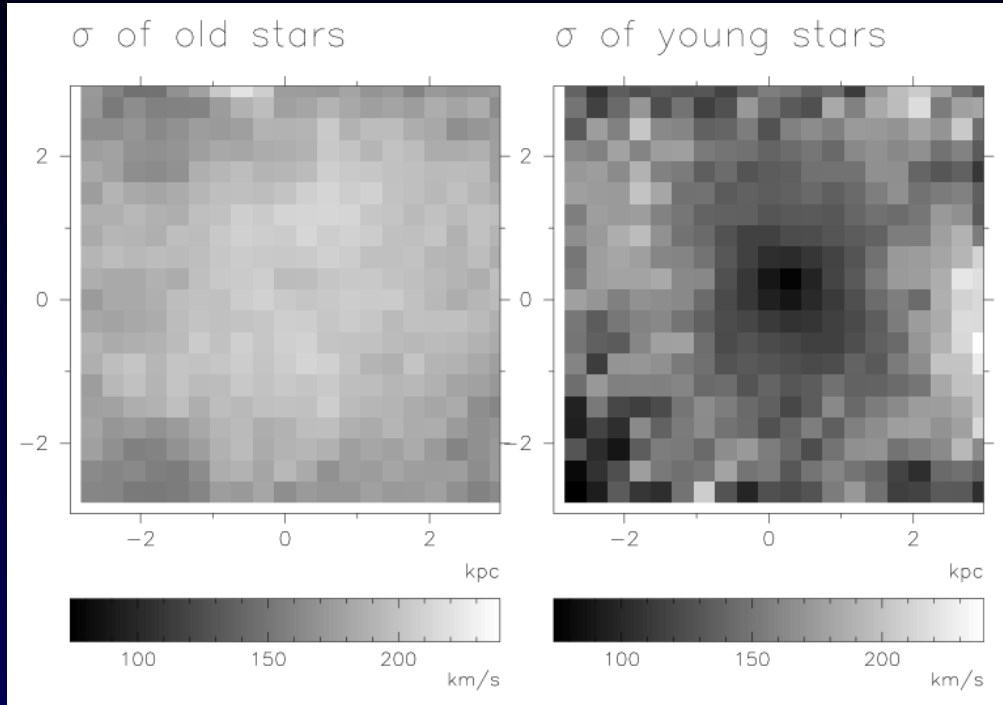
- Focus on data reduction (time constraints & progress)
 - Data reduction issues scrutinized more closely than previously in the course of my science programme to study E+A galaxies
 - After 13 years working with IFU data, reduction still takes months...
- Disclaimer: not all of the problems presented here have a satisfactory solution in the public data reduction package
 - At least one needs a bit more investigation
 - A number are on the “to do” list, pending availability of resources
 - Some have now been solved or can be worked around easily enough
 - Just understanding the problems and systematics is a start...
 - Interpret results accordingly
 - Possibility to implement your own solutions

Science project

- Sample of low- z E+A (post-starburst) galaxies from SDSS
 - Have recently undergone and then abruptly ceased star formation in an otherwise old stellar environment
 - Tantalizing link from star-forming galaxies to the red sequence?
 - Want to distinguish between and understand possible mechanisms leading to this transition and their beginning/end products
- Bekki et al., 2005: numerical simulations of different possible E+A transition scenarios (major+minor mergers, tidal encounters)
 - Models incorporating stellar population synthesis code – predict 2D distribution of line indices and photometry as well as kinematics
- Need accurate velocity measurements for mapping 2D kinematic structure
- Need reliable calibration of flux for mapping variations of line indices etc.

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Science project



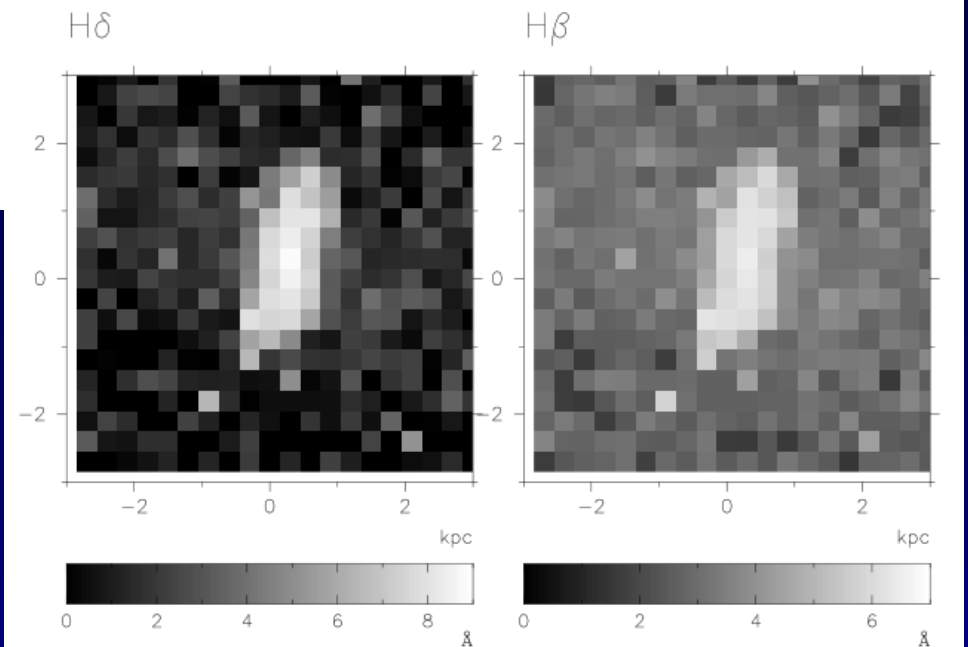
Old stars

Young stars

Bekki et al. (2005),
inclined major merger model

H delta

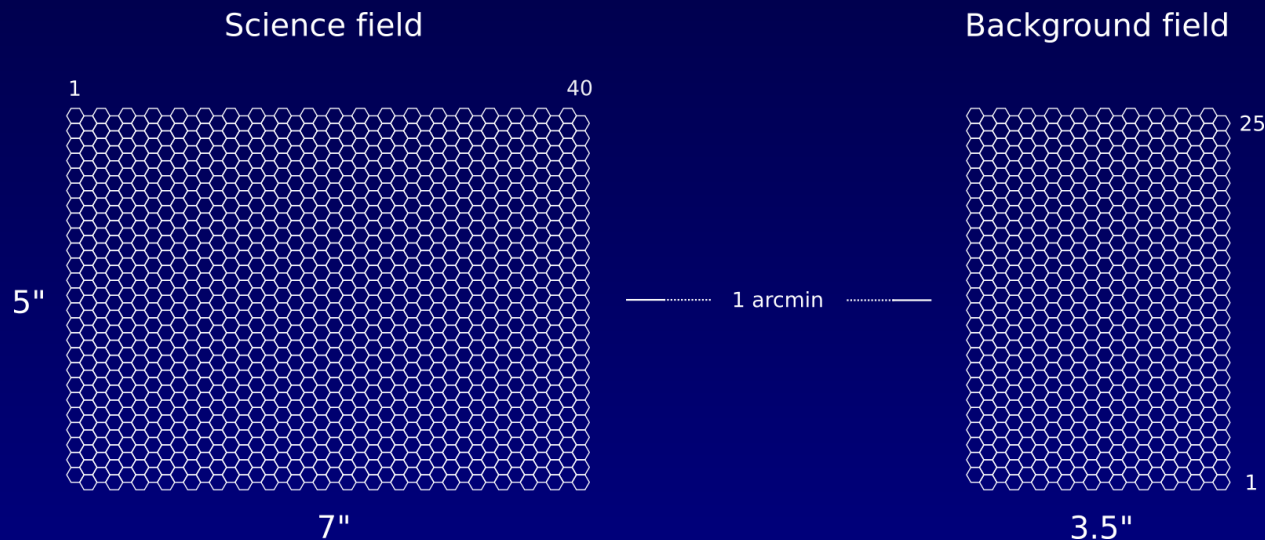
H beta



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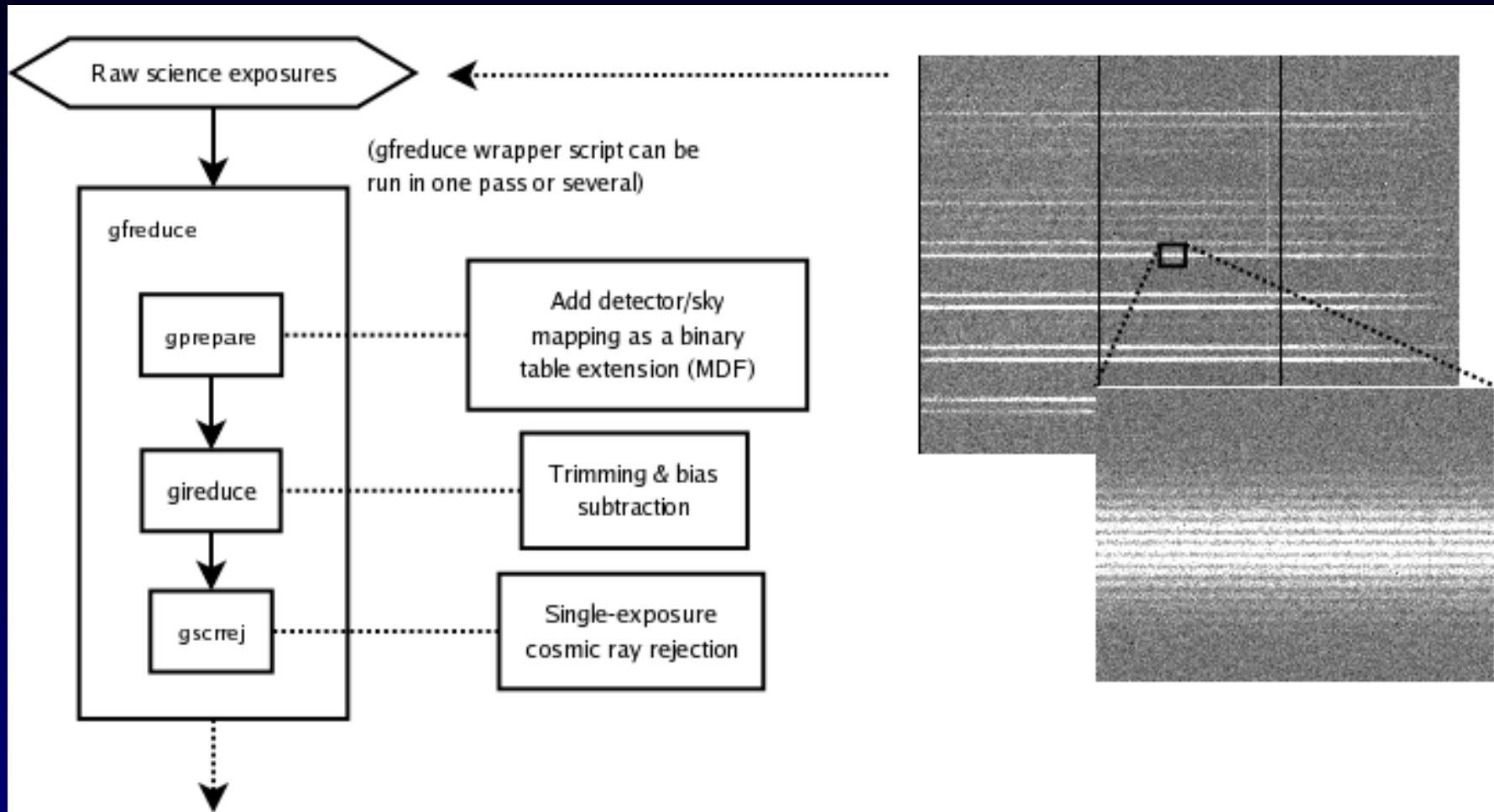
Instrument

- Each Gemini Multi-Object Spectrograph has a deployable fibre-lenslet IFU
 - Mainly used GMOS-N for this project
 - 2-slit mode: each half of the 7x5" field maps to a separate 1D slit on the detector array
 - The 2 slits are stacked in the dispersion direction and separated using bandpass filters
 - Separate background fibres for sky subtraction, mapping to both slits



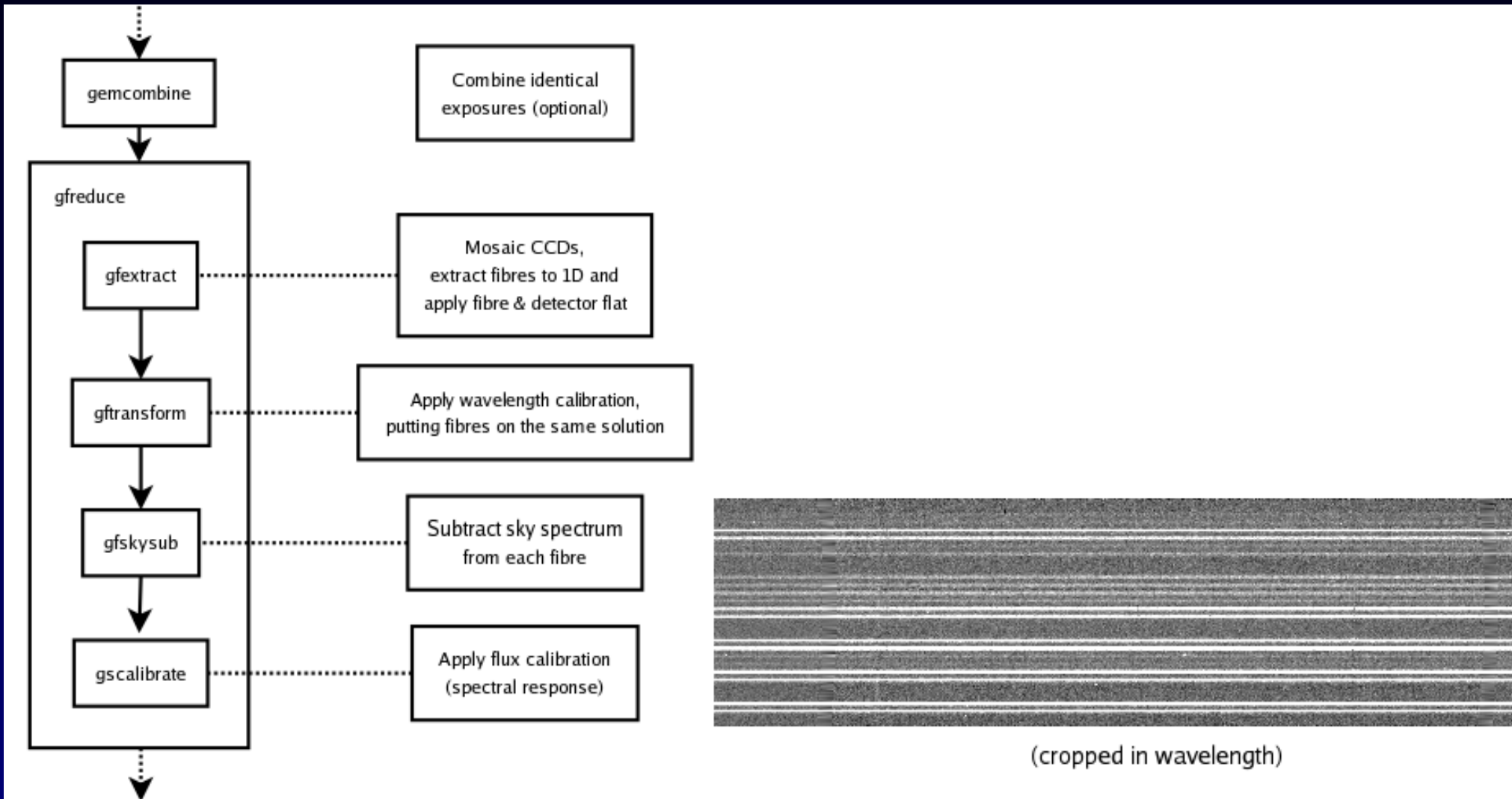
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Typical GMOS DR sequence

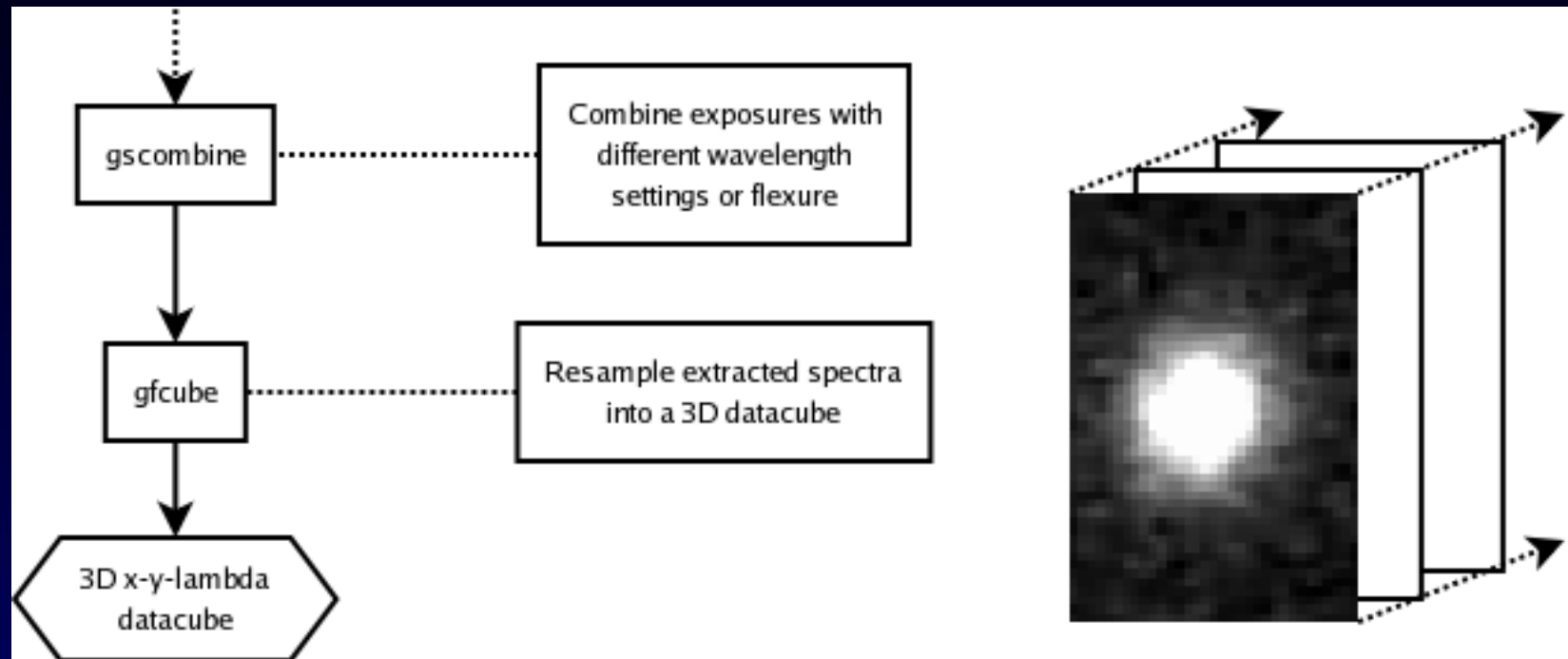


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Typical GMOS DR sequence



Typical GMOS DR sequence



Often works well for quick look reduction...

Won't dwell on how the sequence looks (see GMOS documentation) but rather discuss what to watch out for

Issues to watch out for

- The reduction is mostly problem free except for...

Issues to watch out for

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 - Bias subtraction
 - Scattered light
 - Cosmic ray rejection
 - Fibre extraction
 - Flat fielding
 - QE colour terms
 - Wavelength calibration
 - Sky subtraction
 - Combining wavelength offsets
 - Atmospheric dispersion
 - Mosaicing datacubes
 - Kinematic discontinuities

Issues to watch out for

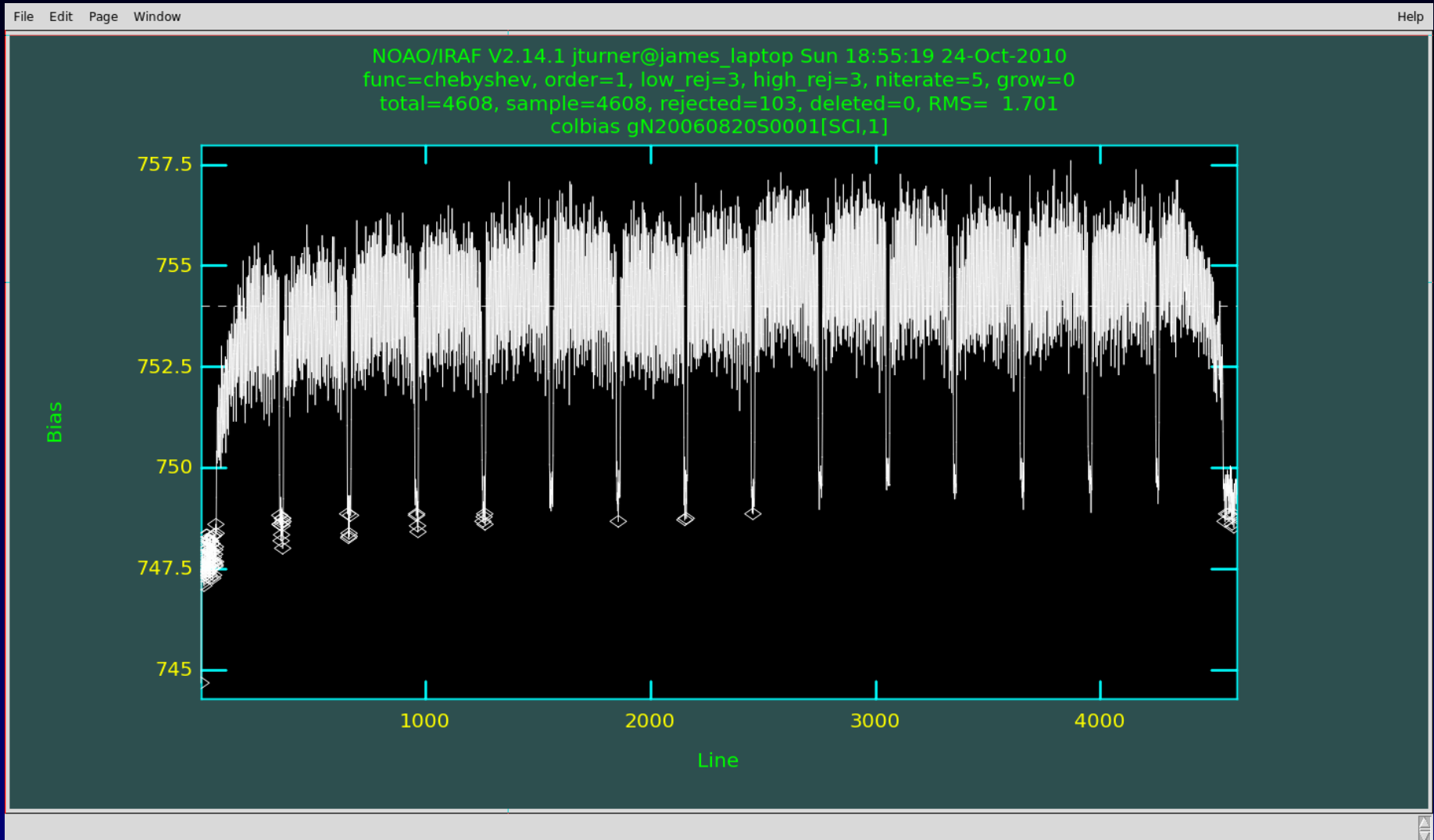
- The reduction is mostly problem free except for...
 - Bias subtraction (solved 😊)
 - Scattered light
 - Cosmic ray rejection
 - Fibre extraction
 - Flat fielding
 - QE colour terms
 - Wavelength calibration
 - Sky subtraction
 - Combining wavelength offsets
 - Atmospheric dispersion (solved 😊)
 - Mosaicing datacubes (available)
 - Kinematic discontinuities

Bias subtraction

- Gemini-processed bias frames may or may not be overscan subtracted
 - The bias level can drift significantly
 - Subtract the overscan from your science data with `fl_over+` and re-process the bias to match if needed
- Ensure you use the right bias! The scripts can be made to use fast readout biases with slow readout science data etc., which won't work properly...
- By default, the closest overscan columns to the science array are excluded (parameter `nbiascontam`), but the remaining columns can still contain significant contamination by left-over charge from the science data.
 - Safest to use only the end rows, where there's no signal!
 - New parameter `biasrows` added for this project (defaults to all rows, as previously)

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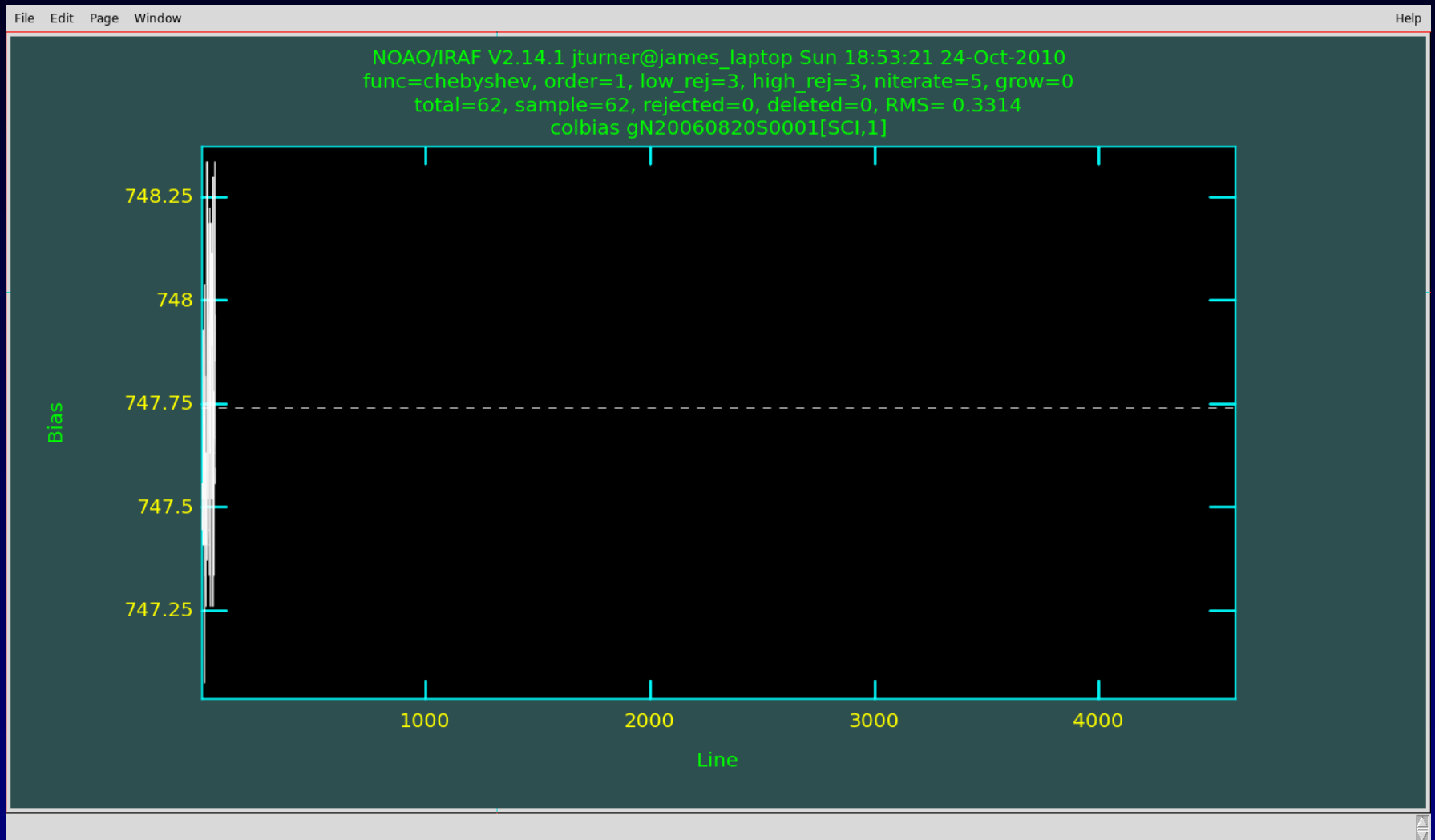
Bias subtraction



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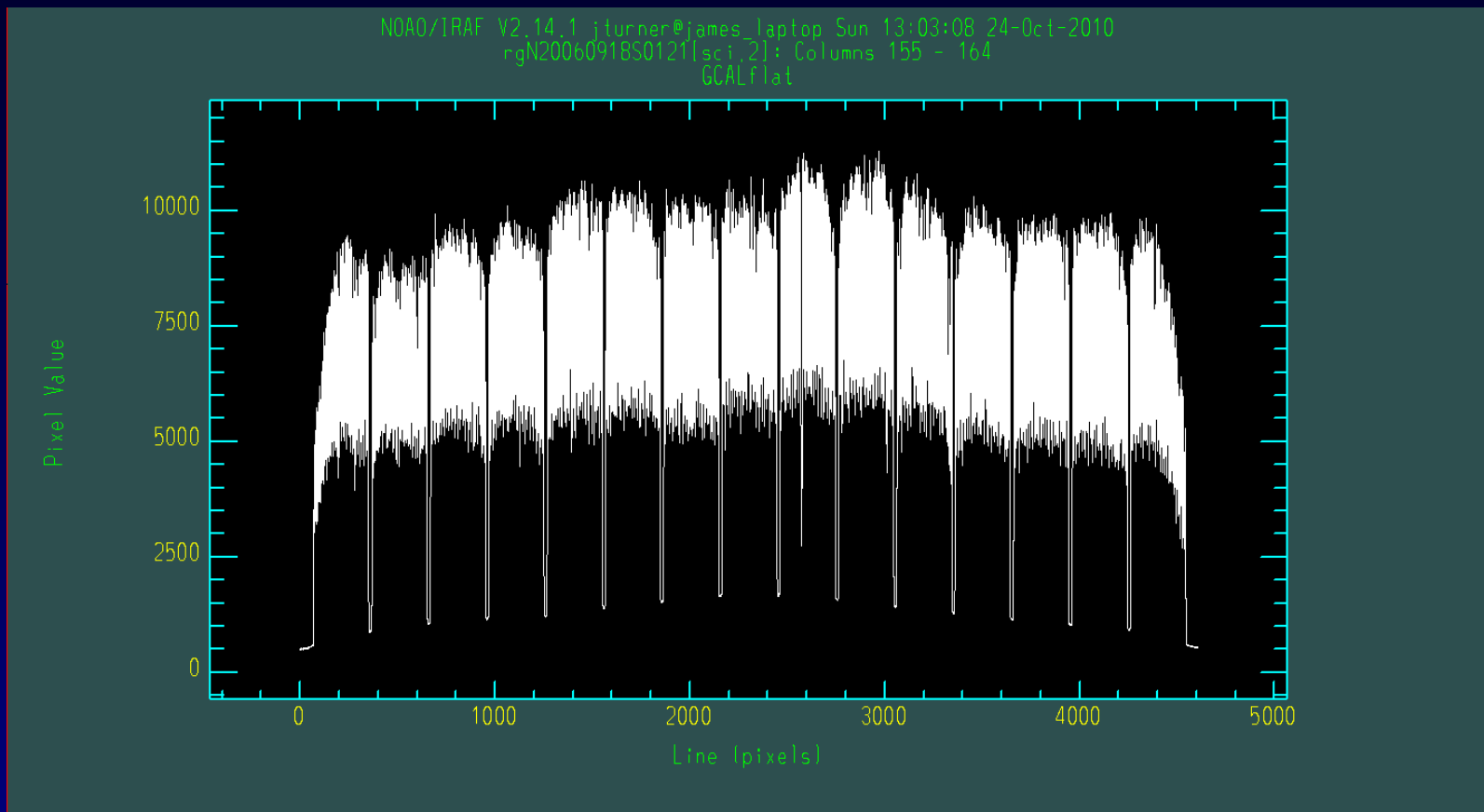
Bias subtraction

- Eg. for GMOS-N, I used `biasrows="3:64"` (gets within ~1 count)



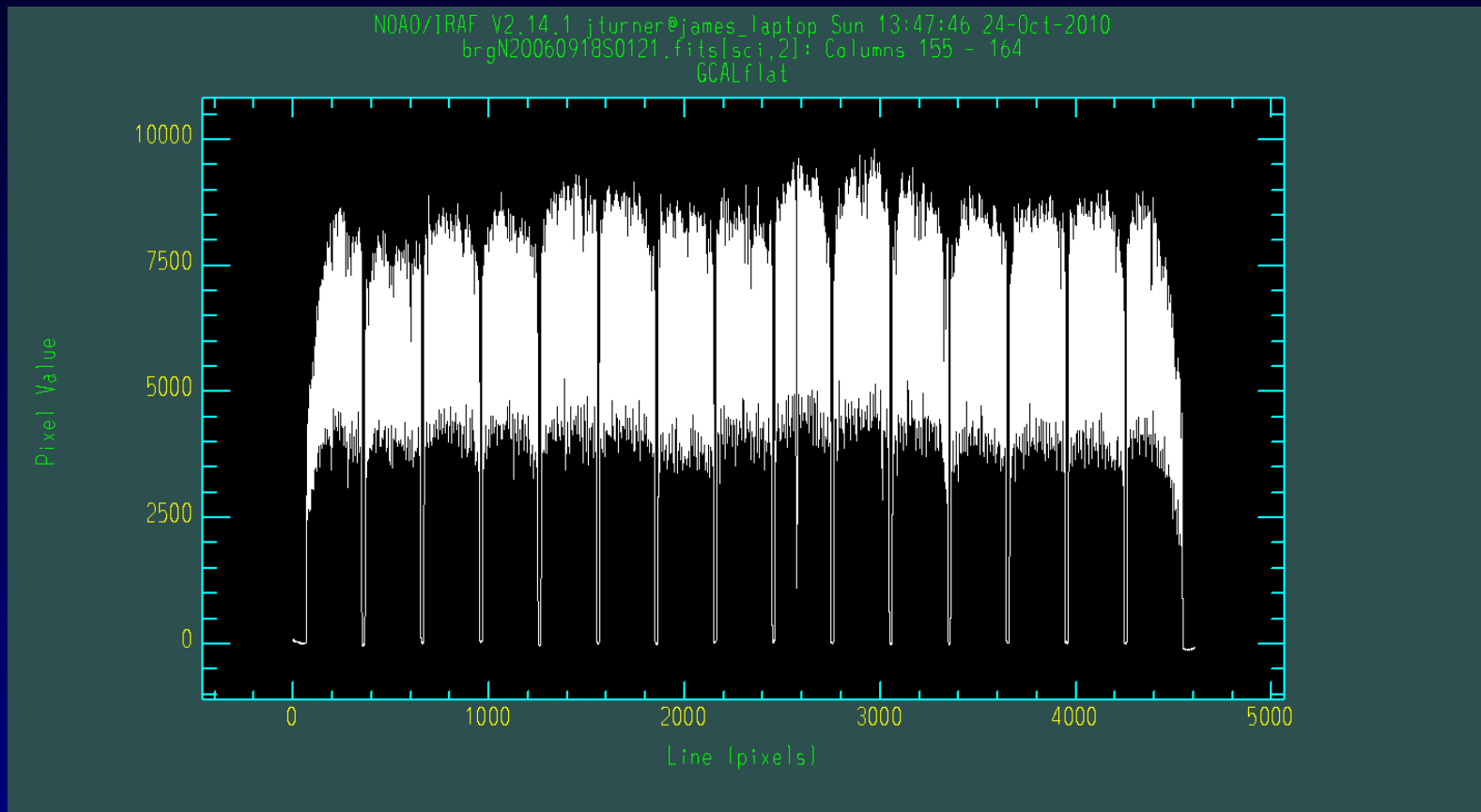
Scattered light

- GMOS data can have a substantial background level between spectra, particularly towards the blue end of GCal flats (where it can reach 20%!):
 - Uncorrected, this distorts the flat fielding etc.



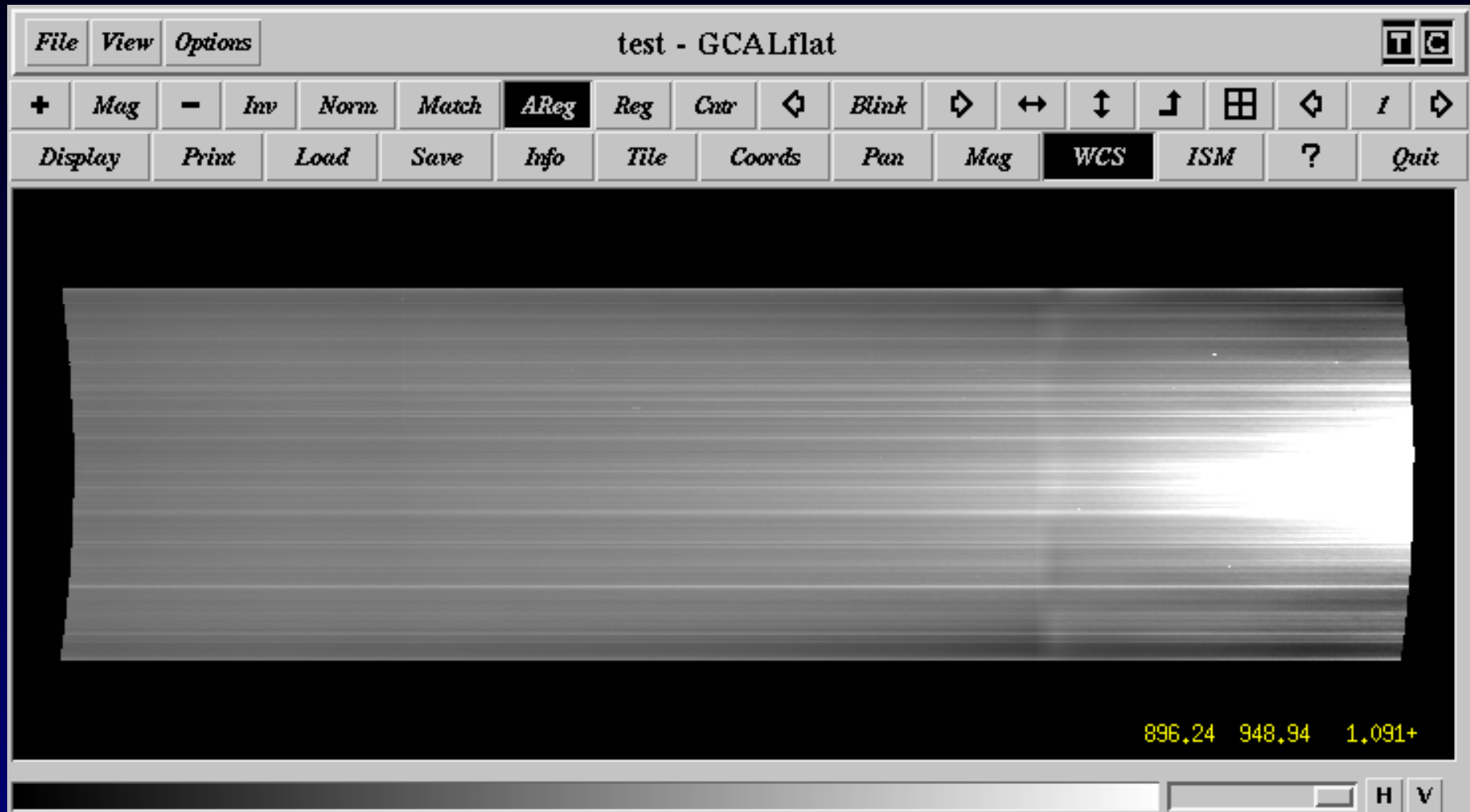
Scattered light

- Model the background with a low-order 2D surface, fitted to the pixel values in between blocks of fibres.
 - Used Bryan Miller's prototype script, `gfbkgsub`, with good results:



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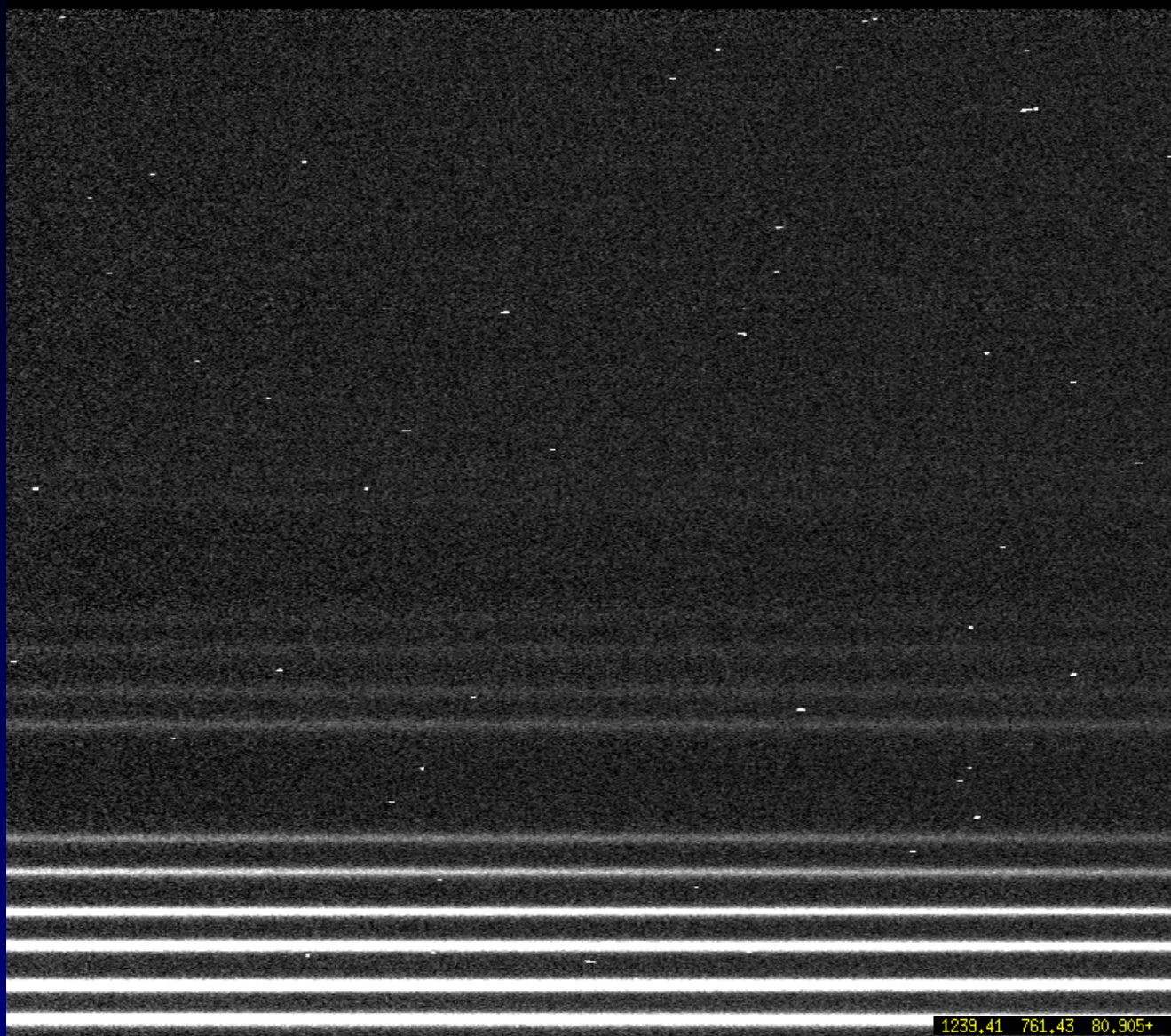
Scattered light



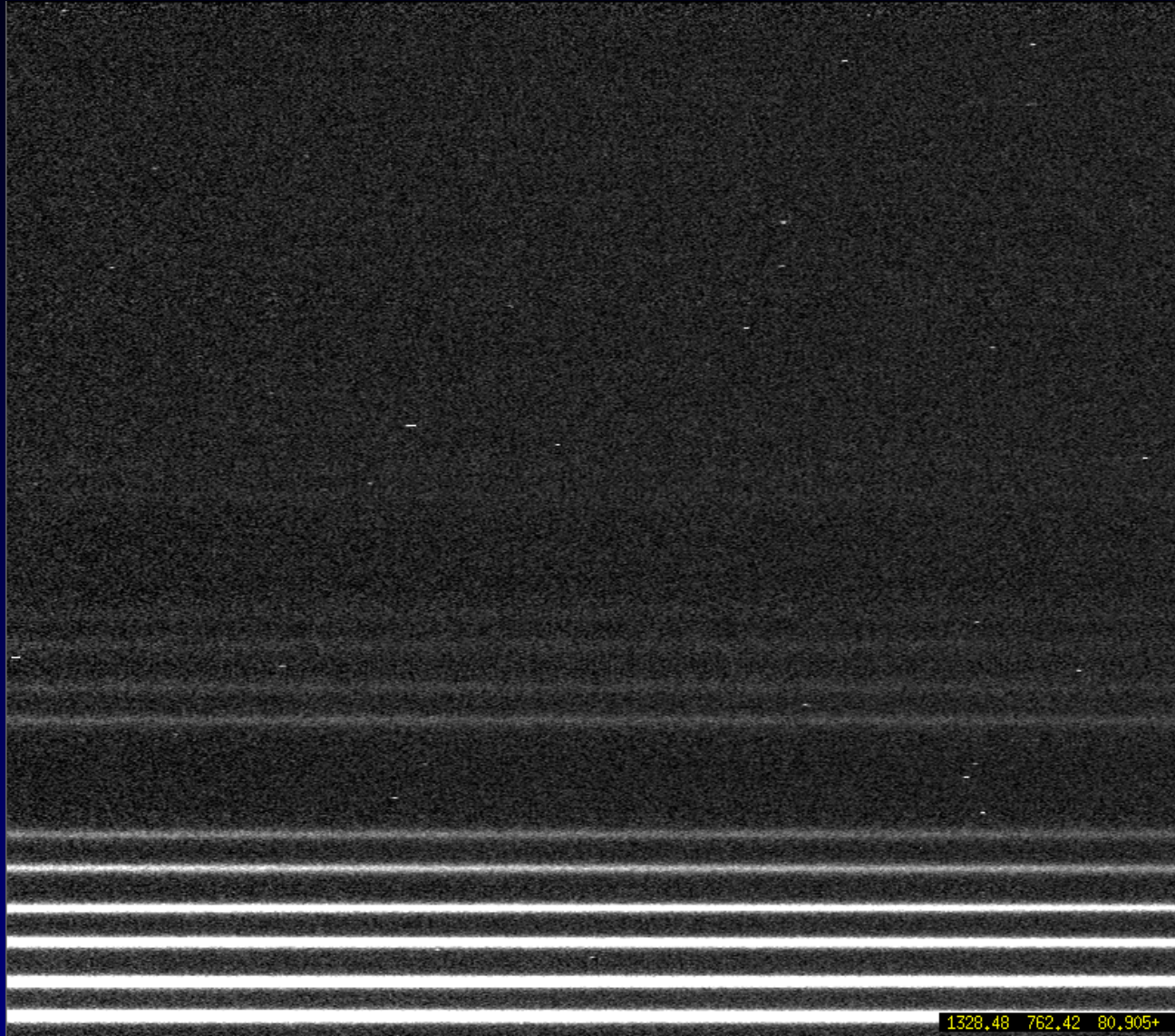
Cosmic ray rejection

- The GMOS package script `gscrrej` was a bit experimental
 - Removes a fair proportion of the cosmic rays, but nowadays better algorithms are available
 - Used LACosmic here (van Dokkum, 2001), wrapped to deal with multi-extension FITS
 - Slow (leave until final pass reduction) but removes the great majority of CRs effectively

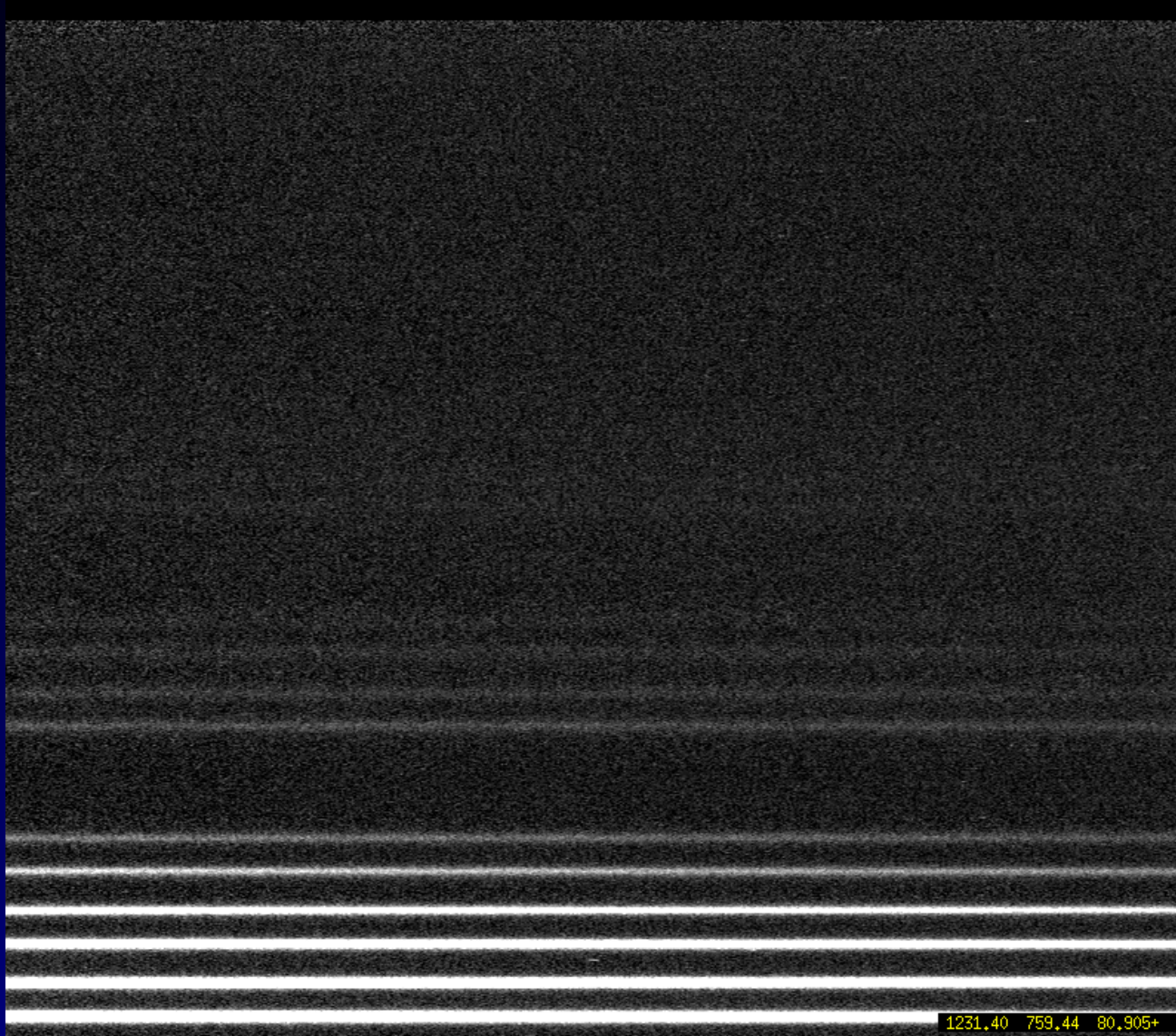
Cosmic ray rejection



Cosmic ray rejection



Cosmic ray rejection



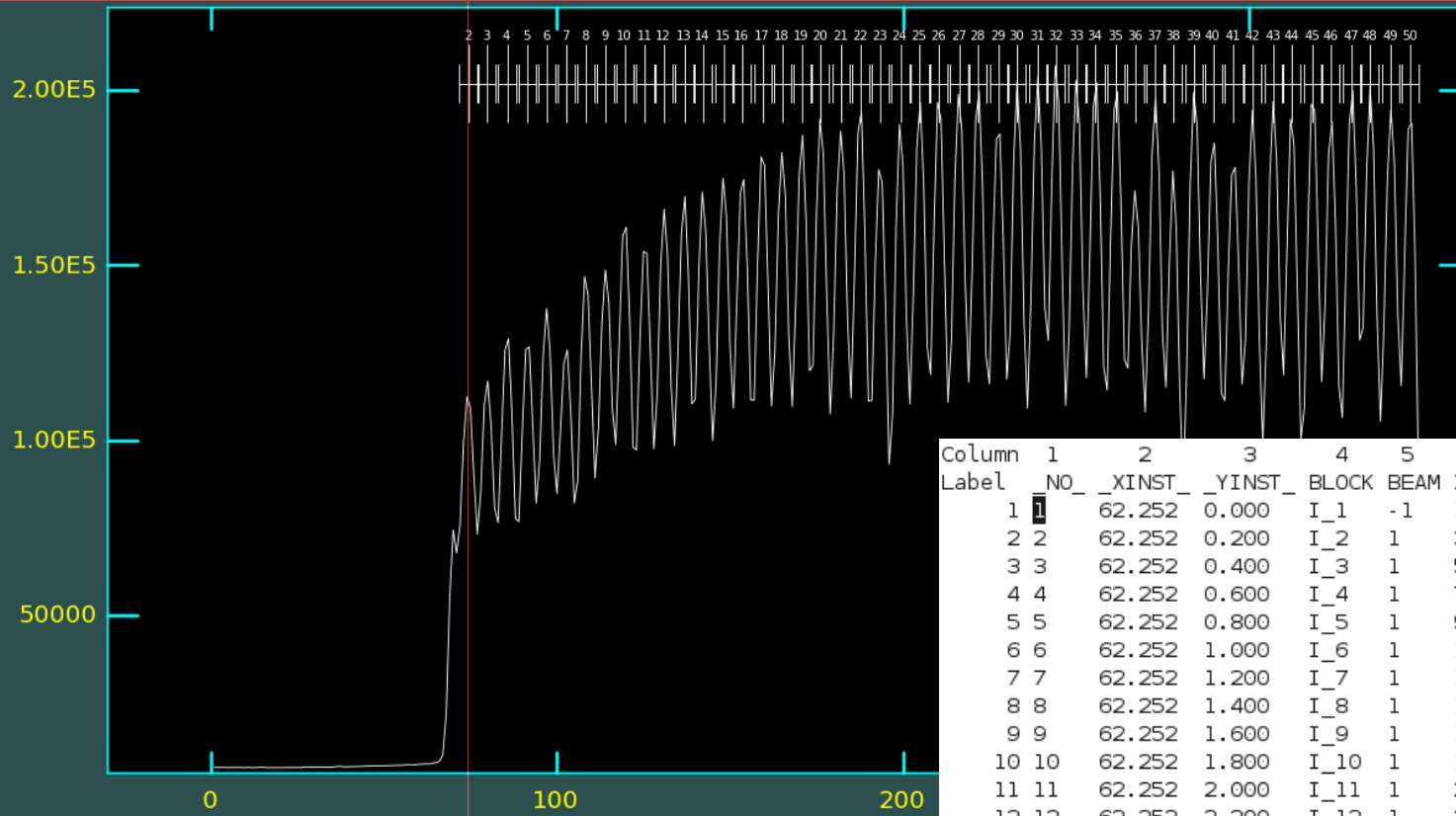
Fibre extraction

- Often all the fibres are identified correctly first time, but not always
 - Eg. flexure can shift the last fibre off the edge of the detector – or a cosmic ray might be misidentified as a fibre.
 - Any error shifts the mapping for all the fibres, distorting the final cube
- Check for problems by doing the initial flat extraction with `gfreduce` interactively
 - Blocks should start at fibre $M*50+1$ and end at $N*50$ (except where the first or last fibre is broken, eg. number 1 for GMOS-N).
 - If any fibres were misidentified, go back and edit the “MDF file” (fibre mapping) with `tables` (eg. `tedit`) to remove missing fibres or change the parameter `line` to avoid artifacts, then re-run the reduction.

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Fibre extraction

NOAO/IRAF V2.14.1 jturner@james_laptop Wed 01:28:02 20-Oct-2010
Image=ergN20060918S0121_1, Sum of columns 1430-1439
Define and Edit Apertures



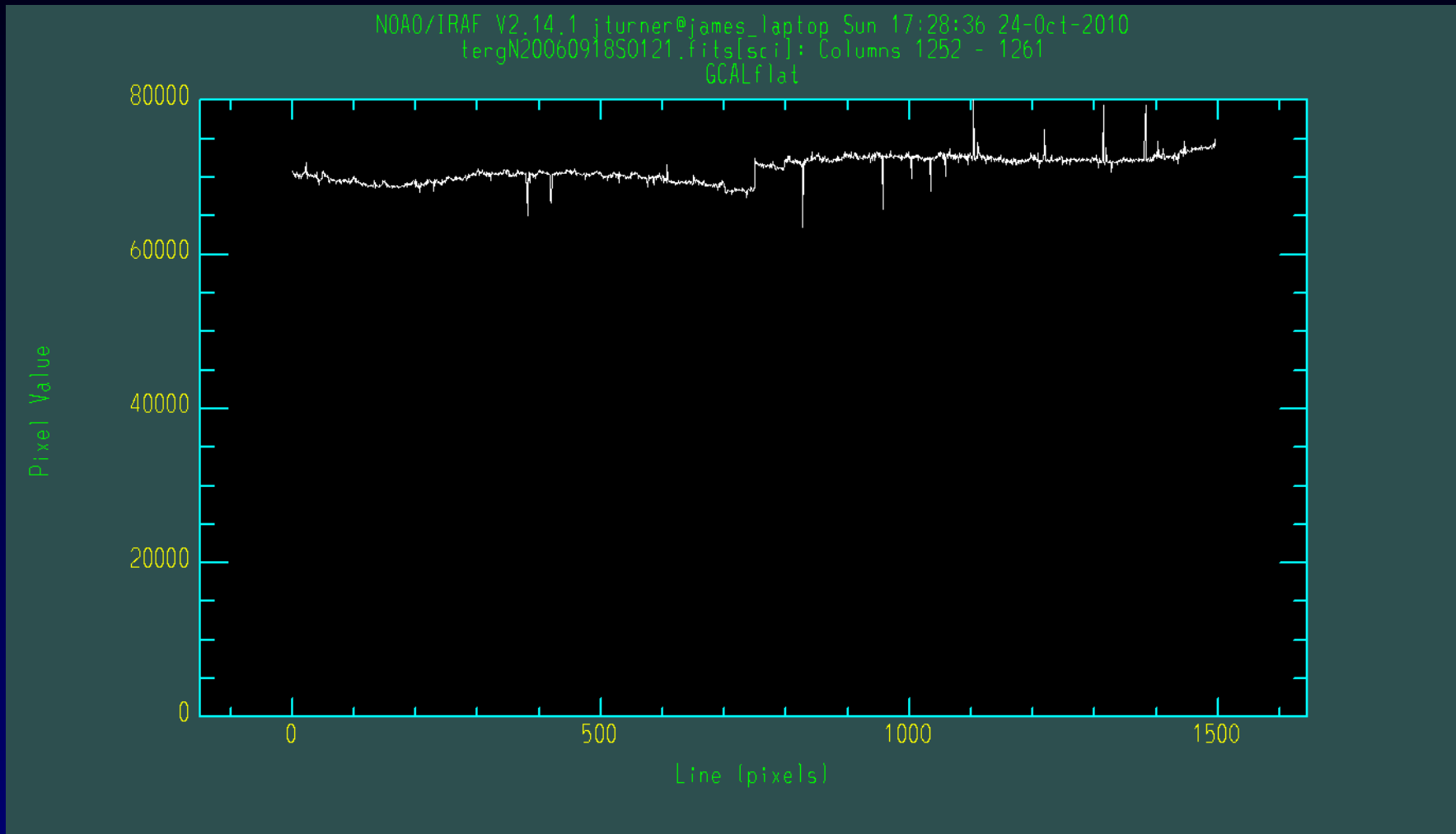
Column	1	2	3	4	5	6	7
Label	NO_	_XINST_	_YINST_	BLOCK	BEAM	XLDIS	YLDIS
1	1	62.252	0.000	I_1	-1	1	16
2	2	62.252	0.200	I_2	1	3	16
3	3	62.252	0.400	I_3	1	5	16
4	4	62.252	0.600	I_4	1	7	16
5	5	62.252	0.800	I_5	1	9	16
6	6	62.252	1.000	I_6	1	11	16
7	7	62.252	1.200	I_7	1	13	16
8	8	62.252	1.400	I_8	1	15	16
9	9	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

Type ^D quit to leave editor, ^D help for help.

Flat fielding

- The current algorithm is susceptible to several sources of error:
 - Continuum normalization doesn't account for distortions
 - Spatial modulation (effectively) over the flat
 - Spatial discontinuity between the slits
 - Relative flexure between science data and twilight flats ignored
 - Leads to erroneously bright and dark single fibres
 - Flat field is applied after interpolation (image mosaicing)
 - Not well justified, though likely quite a small effect
 - Needs more work once Python spectroscopy tools available...
 - (Other, more minor effects buried in my notes)

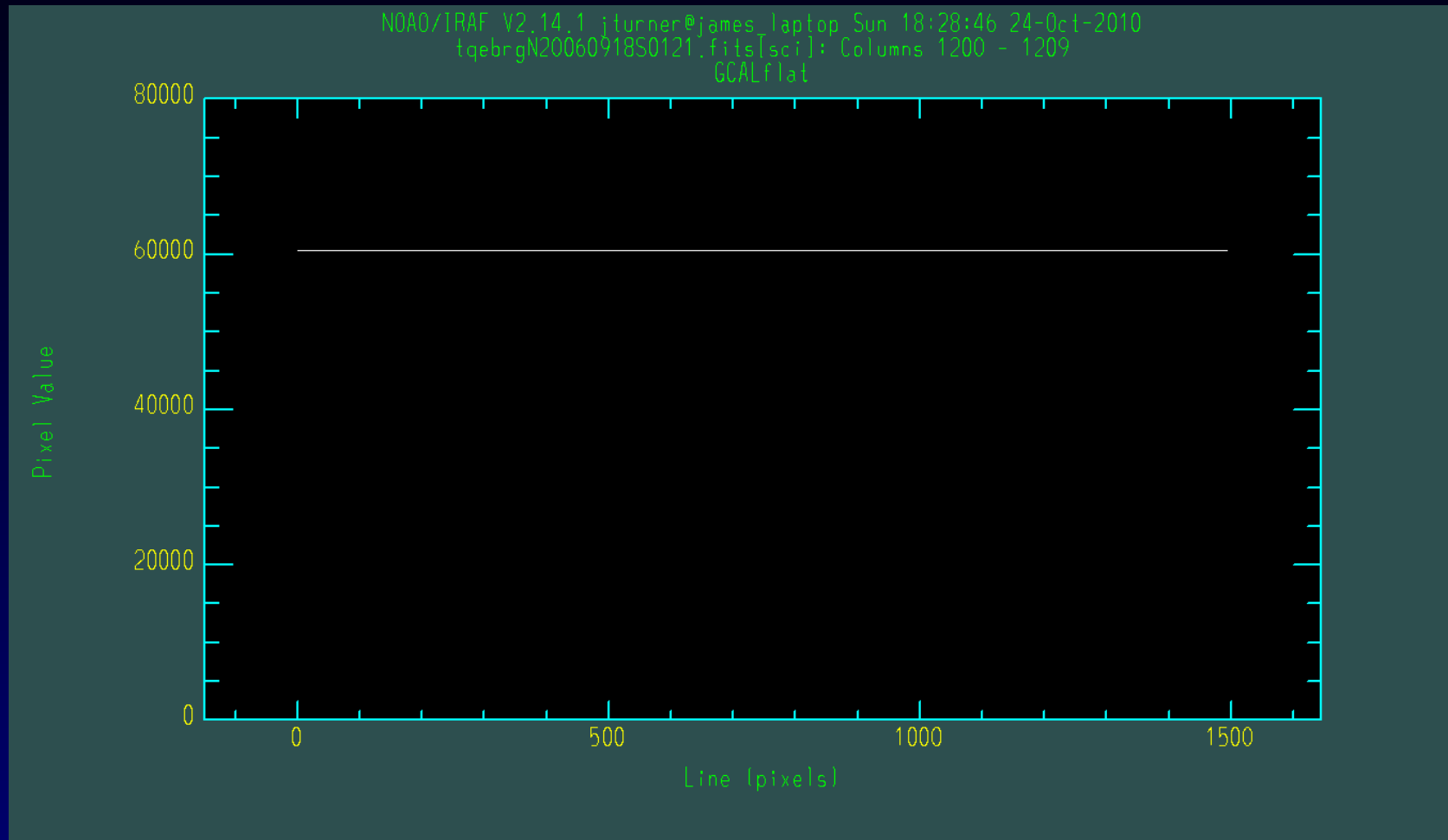
Flat fielding



Flat fielding

- I ended up using the GCal flat only, after modifying the normalization so the continuum fit is matched to the dispersion solution of each individual fibre
 - Some gradual vignetting remains along each slit at the few % level, due to the difference between GCal and sky illumination
 - Not critical here, at least for kinematics
 - Plan to adopt my new continuum normalization method in F2 software

Flat fielding



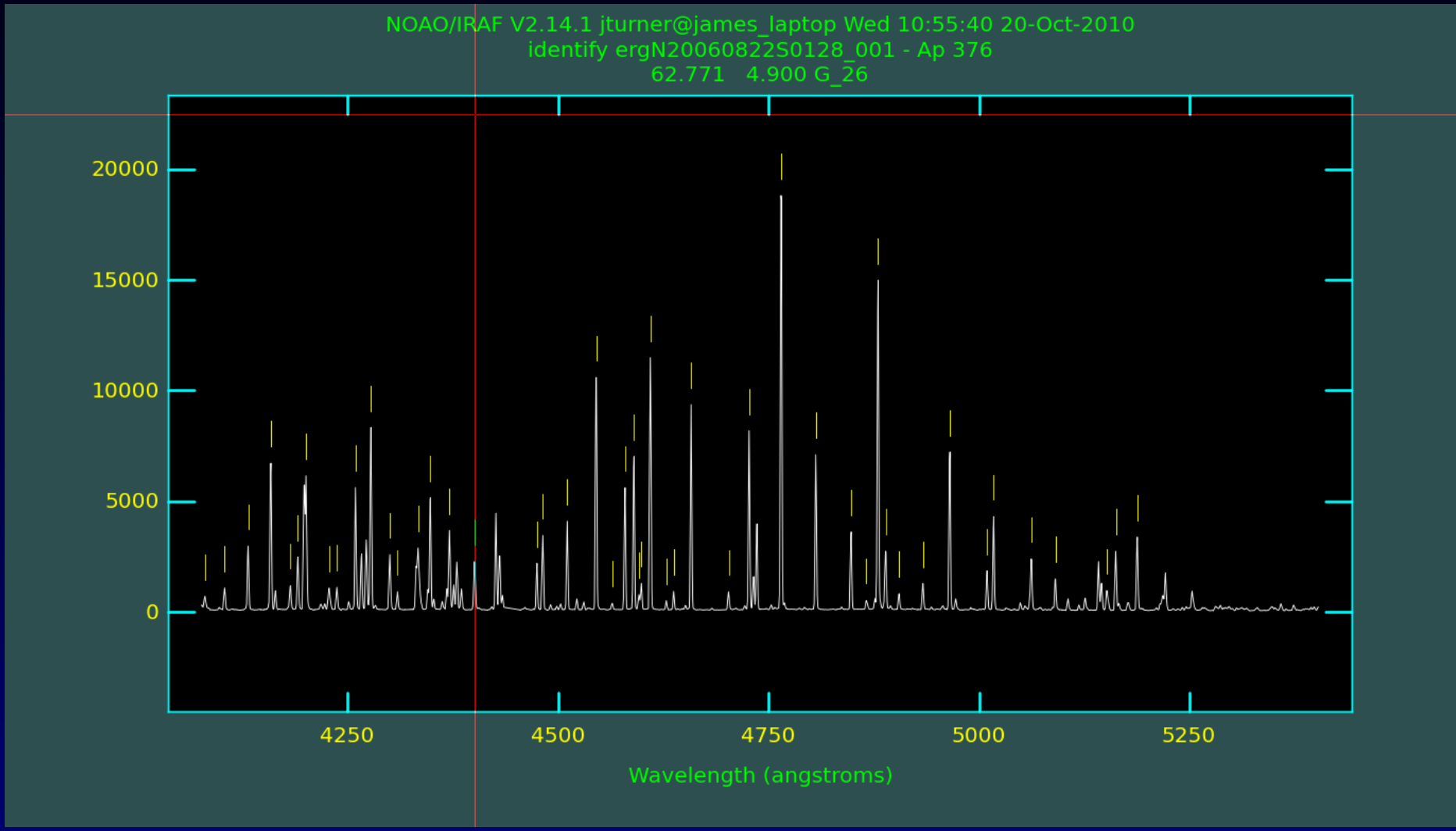
QE colour correction

- The 3 GMOS detectors have different quantum efficiency variations with wavelength
 - Leads to small but discontinuous flux differences between the CCDs
 - Want to compensate for this in both flats and science data (currently not handled by the GMOS package)
 - Otherwise can end up with residual disjoints in the data
 - More serious for GMOS-S (here I'm using GMOS-N, jumps $\leq 2.5\%$)
- Corrected using a prototype script (`qecorr`) and coefficients for $QE(\lambda)$ from Bryan Miller

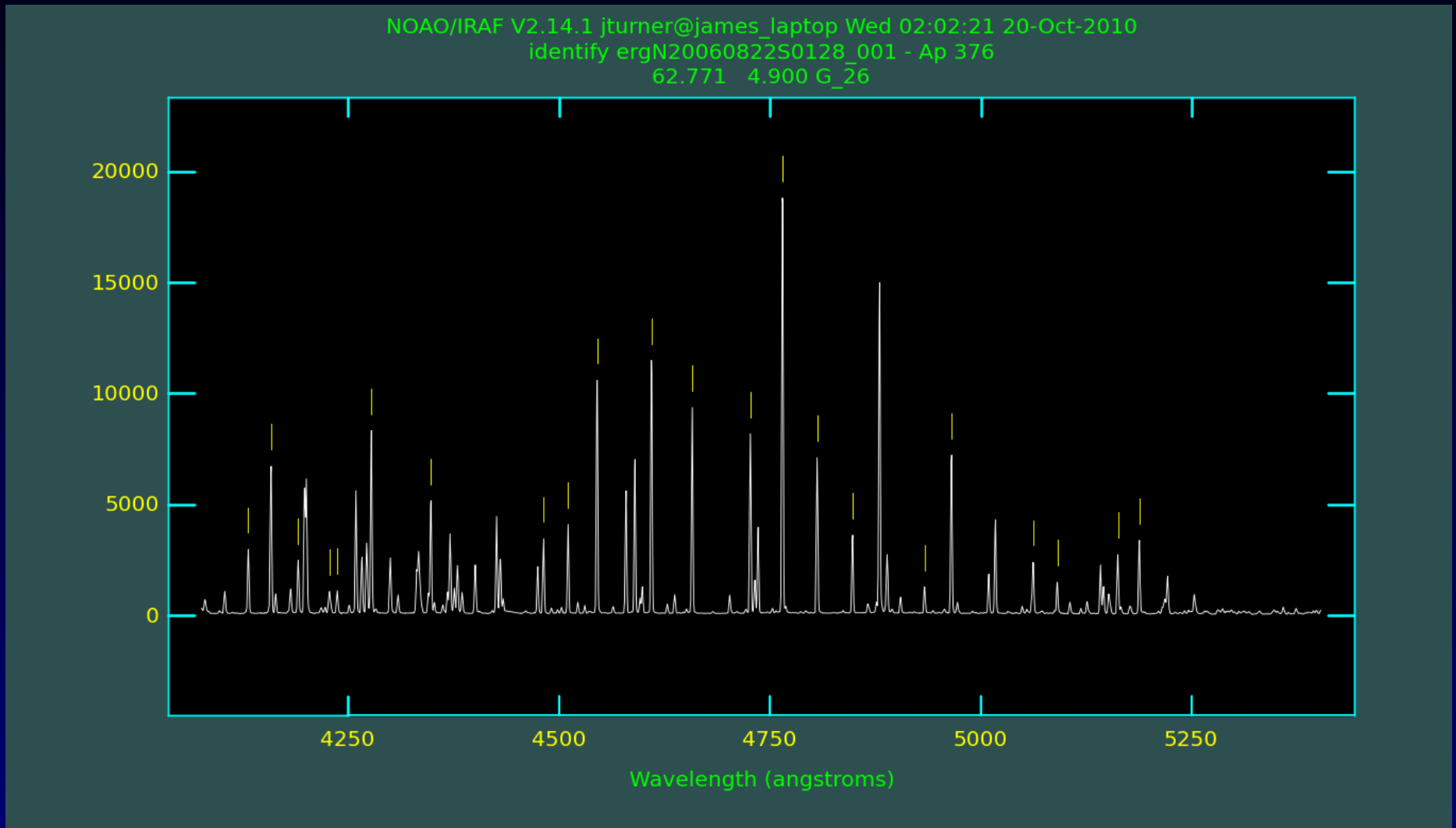
Wavelength calibration

- Sometimes IRAF fails to find lines automatically or makes erroneous identifications
 - Run `gswavelength` interactively on the arc first time
 - Cull the standard line list to avoid problematic identifications before re-running the reduction
- Using the full GMOS/IRAF line list, the fit RMS turns out poorer than expected (a large fraction of a pixel)
 - Select only the brightest ~20 lines from the list to get ~1/20 pix RMS
 - Will come back to why this happens...

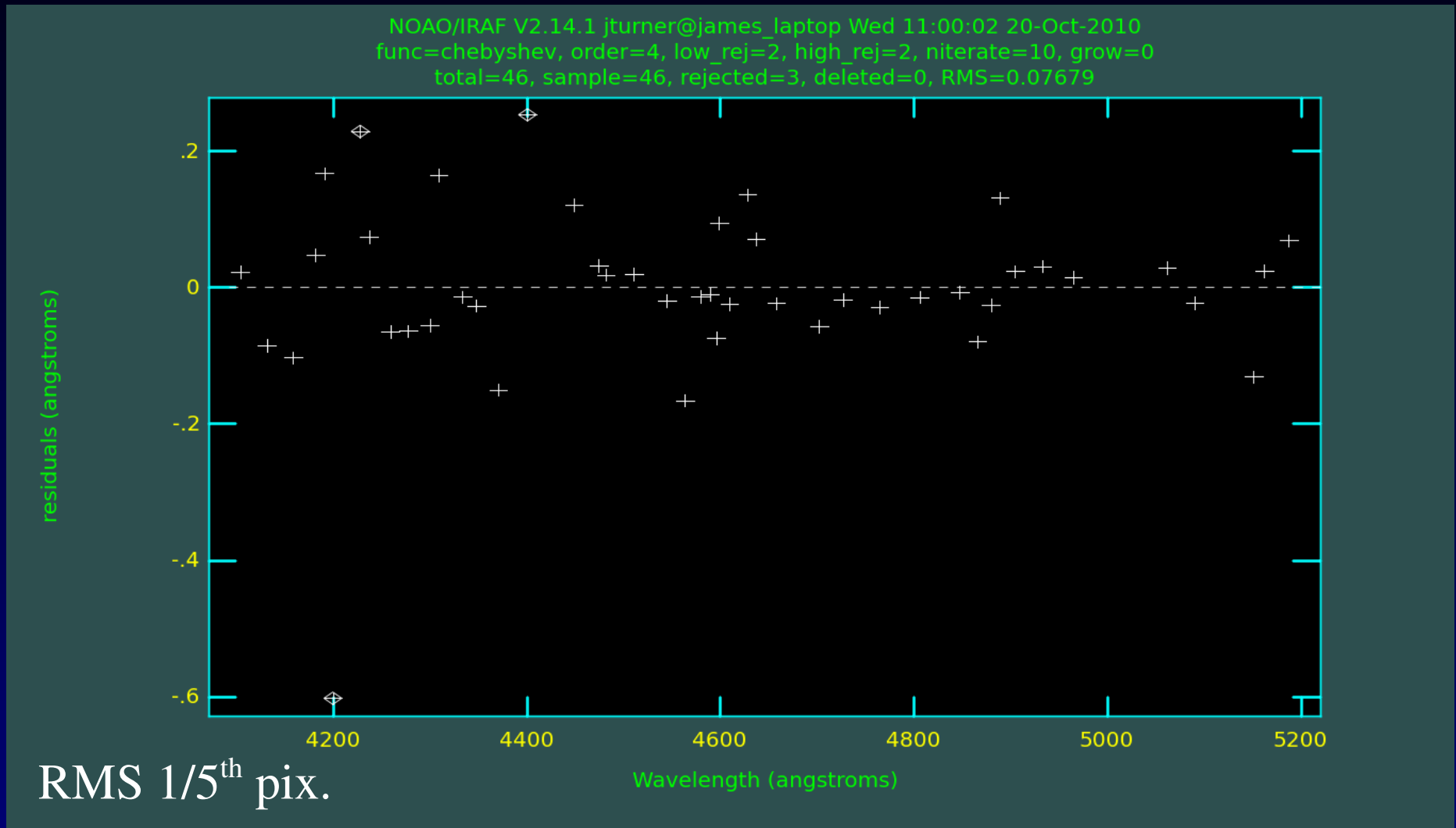
Wavelength calibration



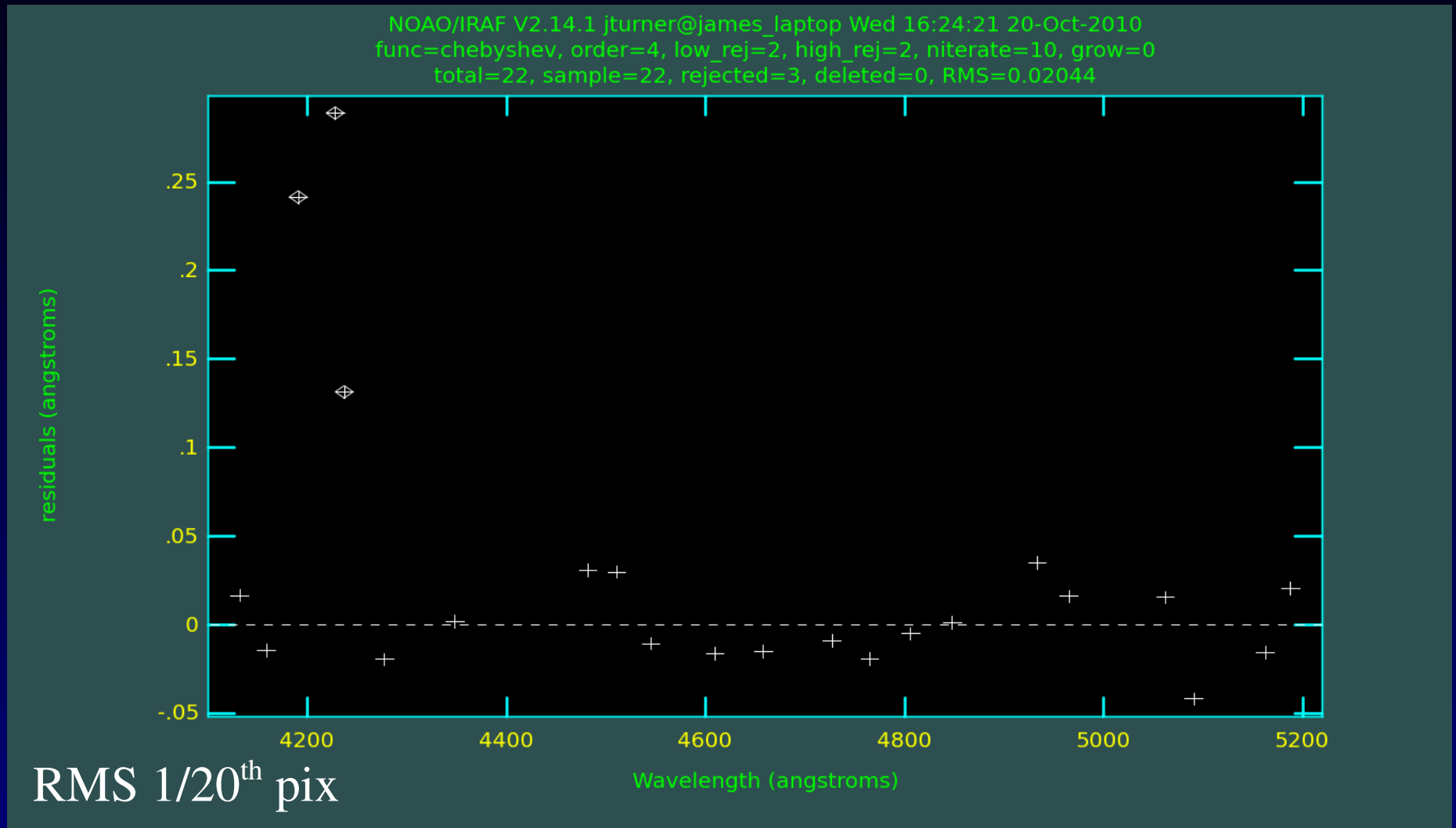
Wavelength calibration



Wavelength calibration

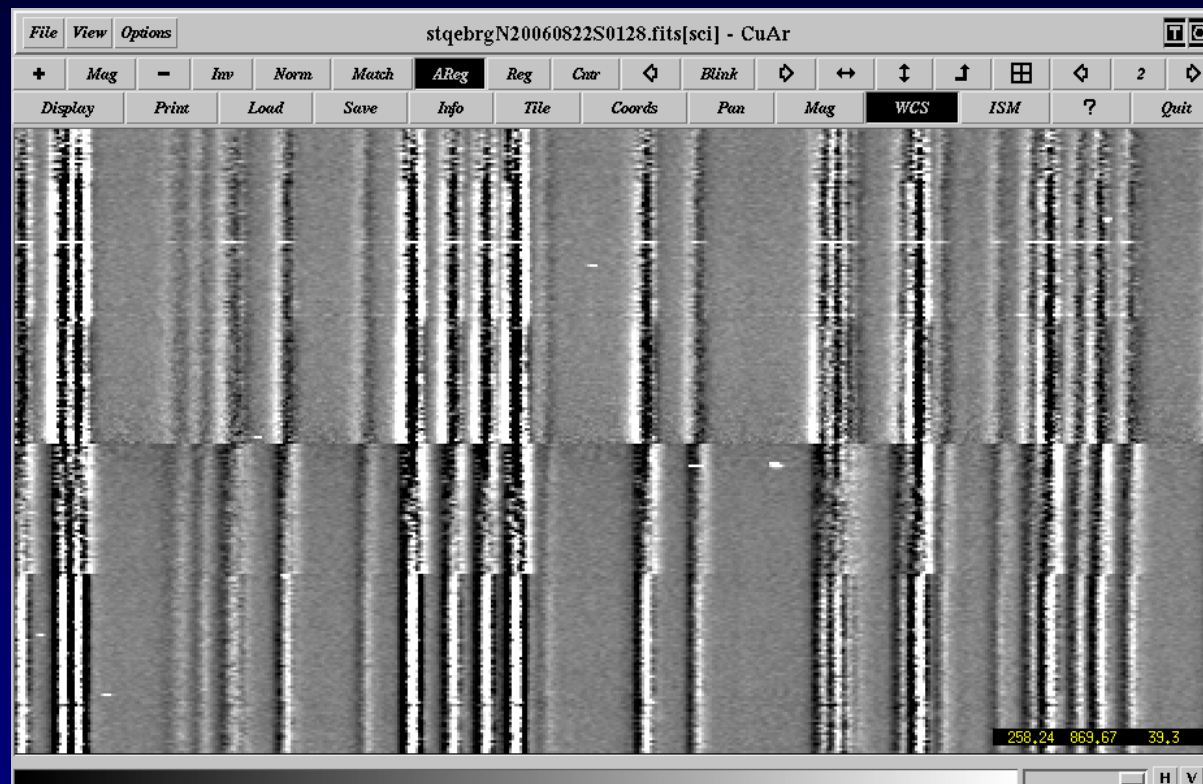


Wavelength calibration



Sky subtraction

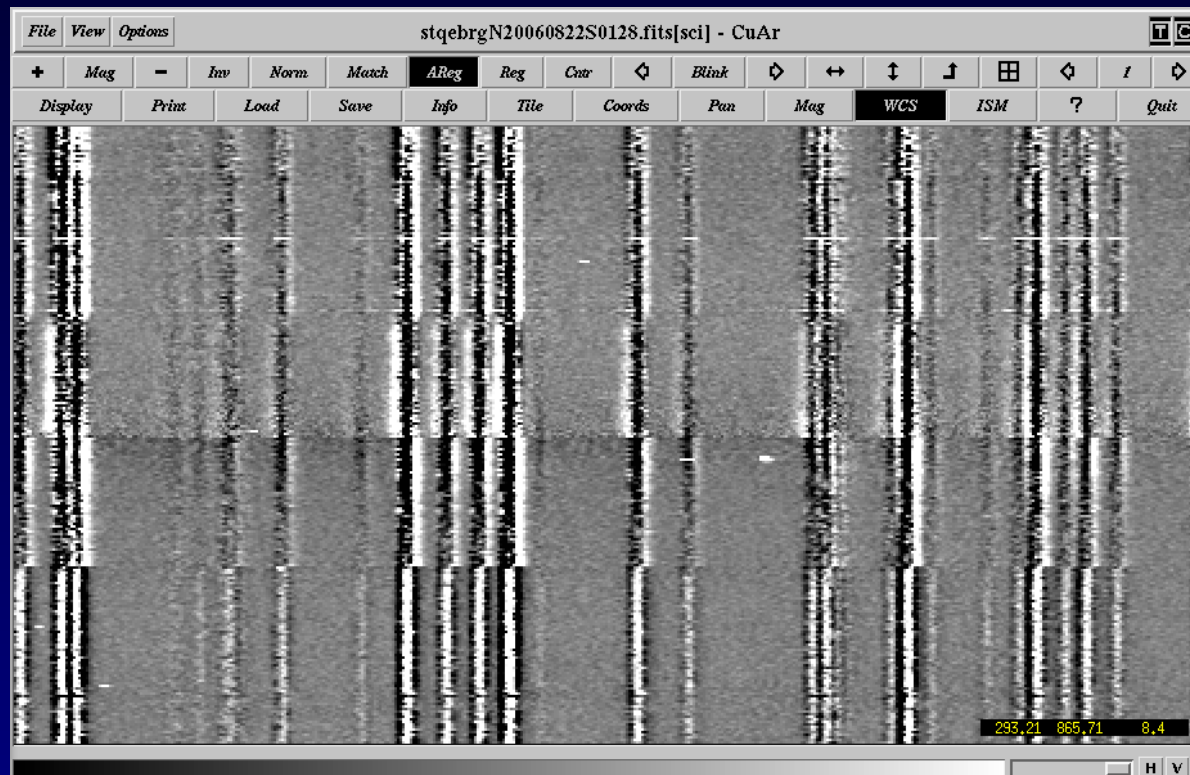
- End up with some (roughly) P-Cygni-type residuals at sky-lines
 - Some residuals probably inevitable with varying fibre PSFs, but notice systematic differences between the slits
 - “Sky subtracted” arc:



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Sky subtraction

- Modified reduction to subtract sky from each slit separately (more on why this is needed later):
 - Residuals didn't go away, but are reduced, esp. for fainter lines
 - Could do with a bit more work, but here I'm observing in the blue



Wavelength dithers

- Common practice to dither the central wavelength, “filling in” CCD gaps
 - No example in the documentation of how to combine the resulting data
 - Want a wrapper for `scombine` (`/lscombine`), to handle MEF files
 - Bryan's scripts include a task, `gscombine`, that is currently unreleased
 - Alternatively, one can use my datacube mosaicing script (more later)

Atmospheric dispersion

- Causes the centring of the IFU on the sky to vary with wavelength
 - Error can be $>1''$ at higher airmass: large compared with $\sim 0.5''$ resolution and $7 \times 5''$ max. FOV
 - Vectors along the spectral axis actually skewed spatially, possibly distorting/elongating 2D maps
- Solved for this project by modelling the atmospheric dispersion with SLALIB and correcting for the estimated shifts when making the datacube
 - New `gfcube` already available in the public Gemini package
 - Use `fl_atmdisp+`
 - Appears to be accurate to $\sim 0.1''$ (half a fibre)

Atmospheric dispersion

Uncorrected: 4100Å



Corrected: 4100Å



Airmass=1.18

Atmospheric dispersion

Uncorrected: 5350Å



Corrected: 5350Å

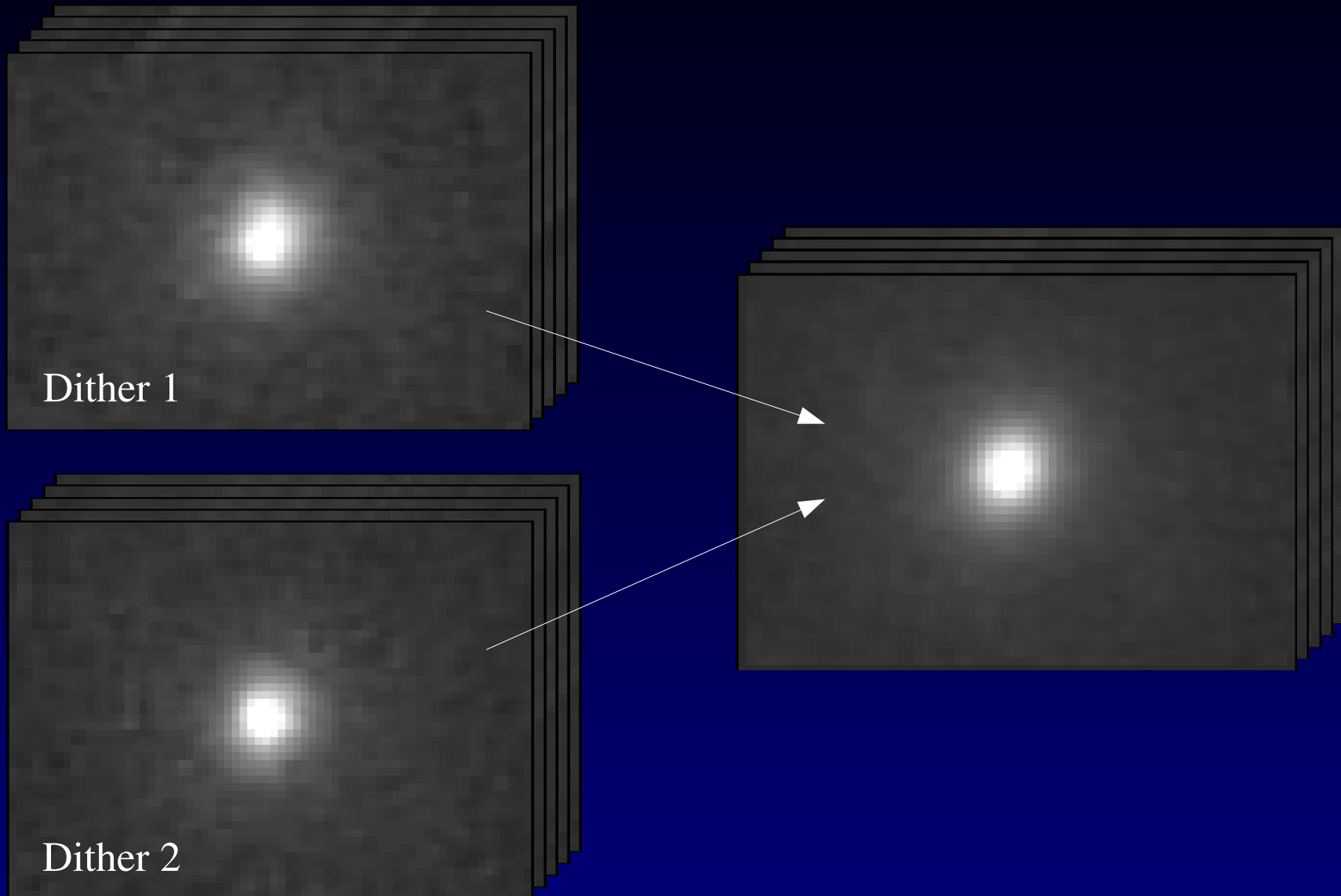


Airmass=1.18

Mosaicing datacubes

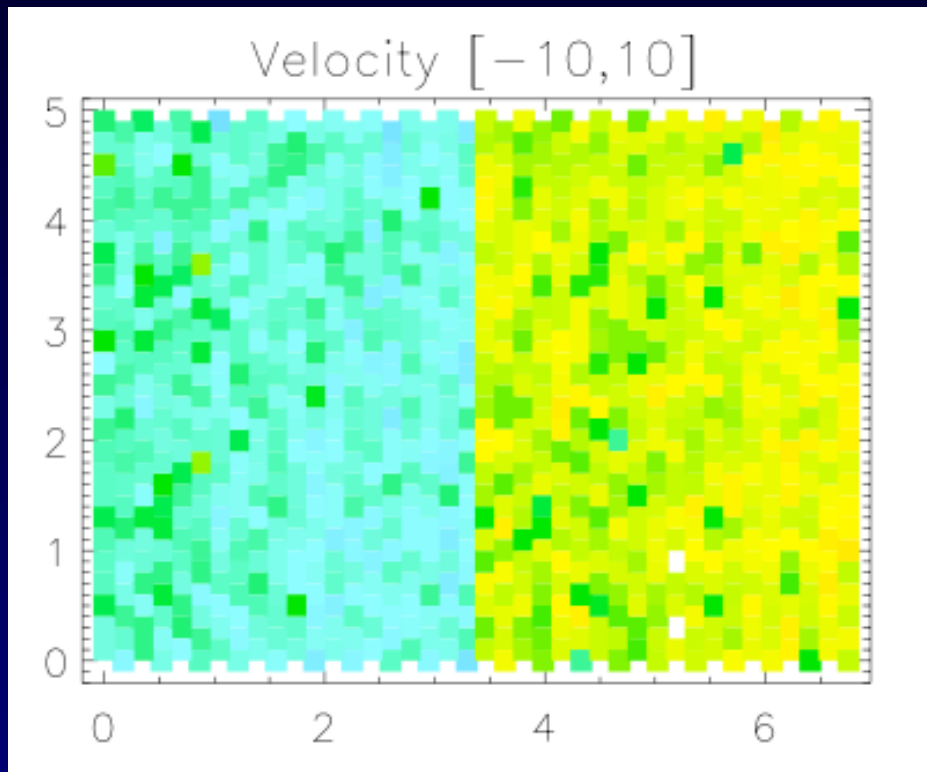
- Exposures are often taken with different telescope pointings:
 - Dithering to smooth over flat field / PSF errors
 - Re-acquisition on different nights
 - Covering a larger FOV
 - Different airmasses ...
- Want 3D mosaicing capability to combine the data (not included in package)
 - Used my `pyfalign` / `pyfmosaic` prototype Python scripts
 - ✓ Can handle wavelength dithers, different PAs etc.
 - ✗ Some low-level artifacts in the edge rows
 - ✗ Automatic alignment of cubes currently very basic
 - ✗ Version with pixel rejection etc. still development
 - Just let me know if you want a copy...

Mosaicing datacubes



Kinematic discontinuities

- A number of people have reported seeing strong systematic discontinuities (up to 15km/s) in velocity fields with the 2-slit IFU mode
 - Bad news for detailed velocity structure in moderately faint galaxies

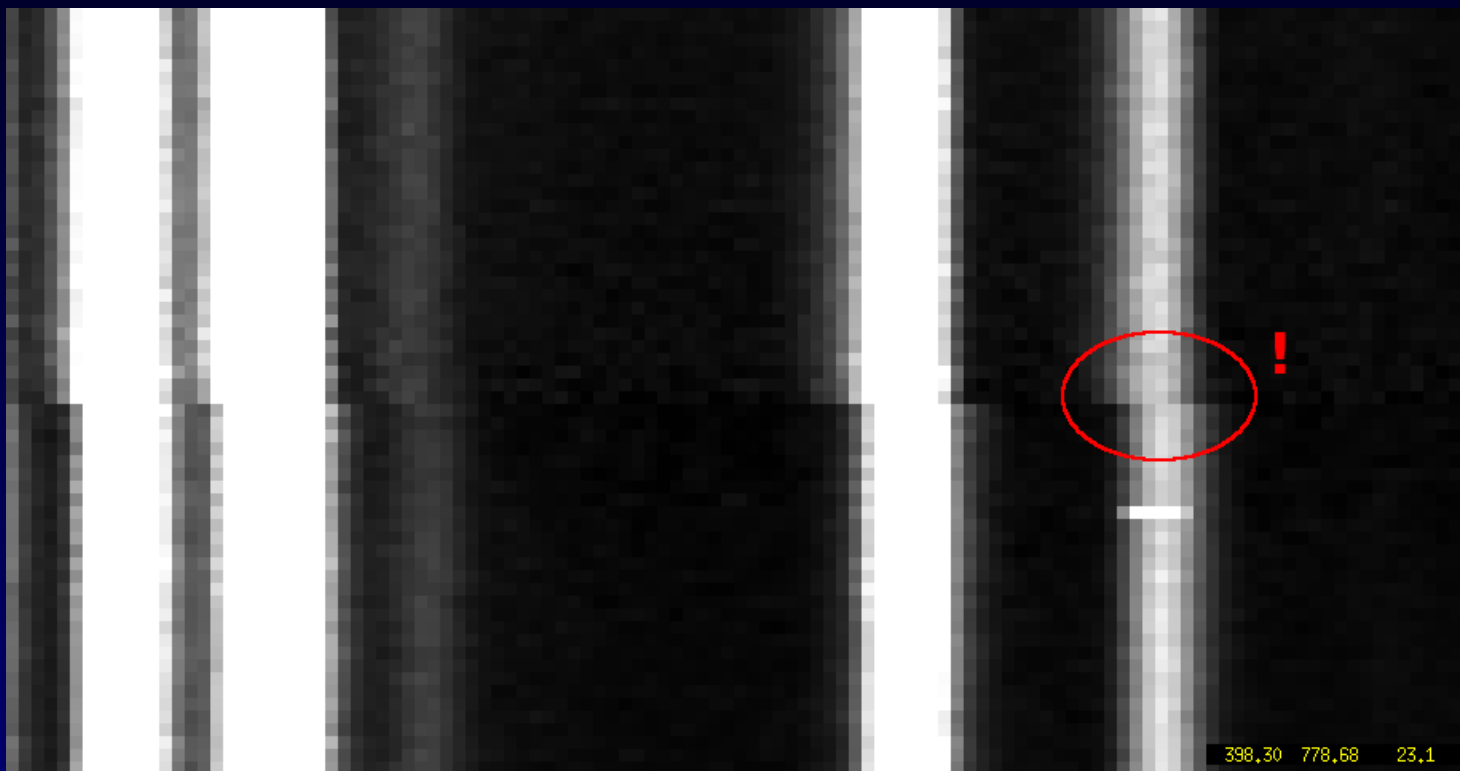


“Velocity” difference of a few km/s between the 2 GMOS IFU slits, derived from a twilight spectrum

(M. Maier D.Phil. thesis, 2008)

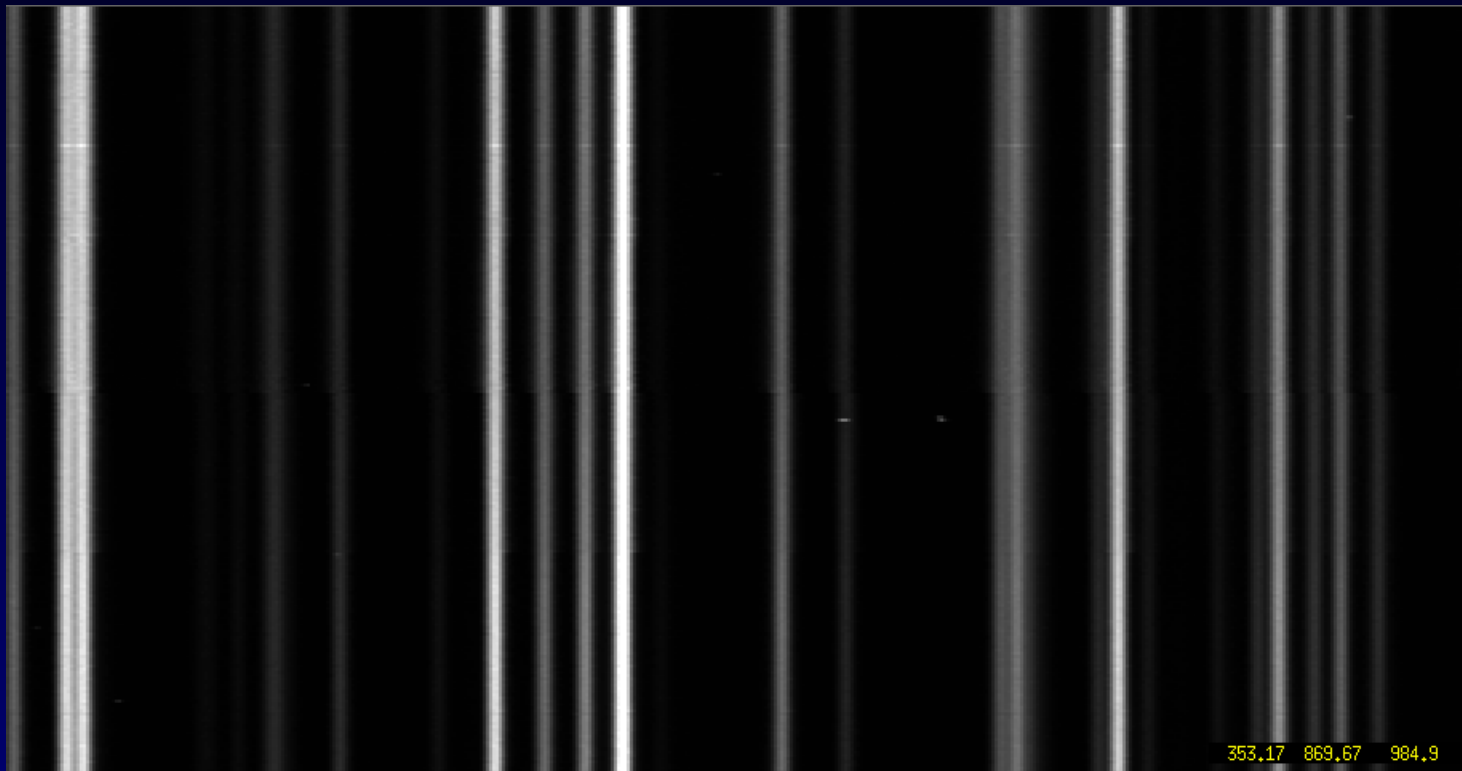
Kinematic discontinuities

- In fact, disjoints between the 2 IFU slits are clearly visible in a wavelength-rectified arc spectrum:



Kinematic discontinuities

- But not for the brightest lines (same exposure, different stretch):



Kinematic discontinuities

- What's wrong with the wavelength calibration?
 - (After *much* investigation) Nothing!
 - Must be the data!

Kinematic discontinuities

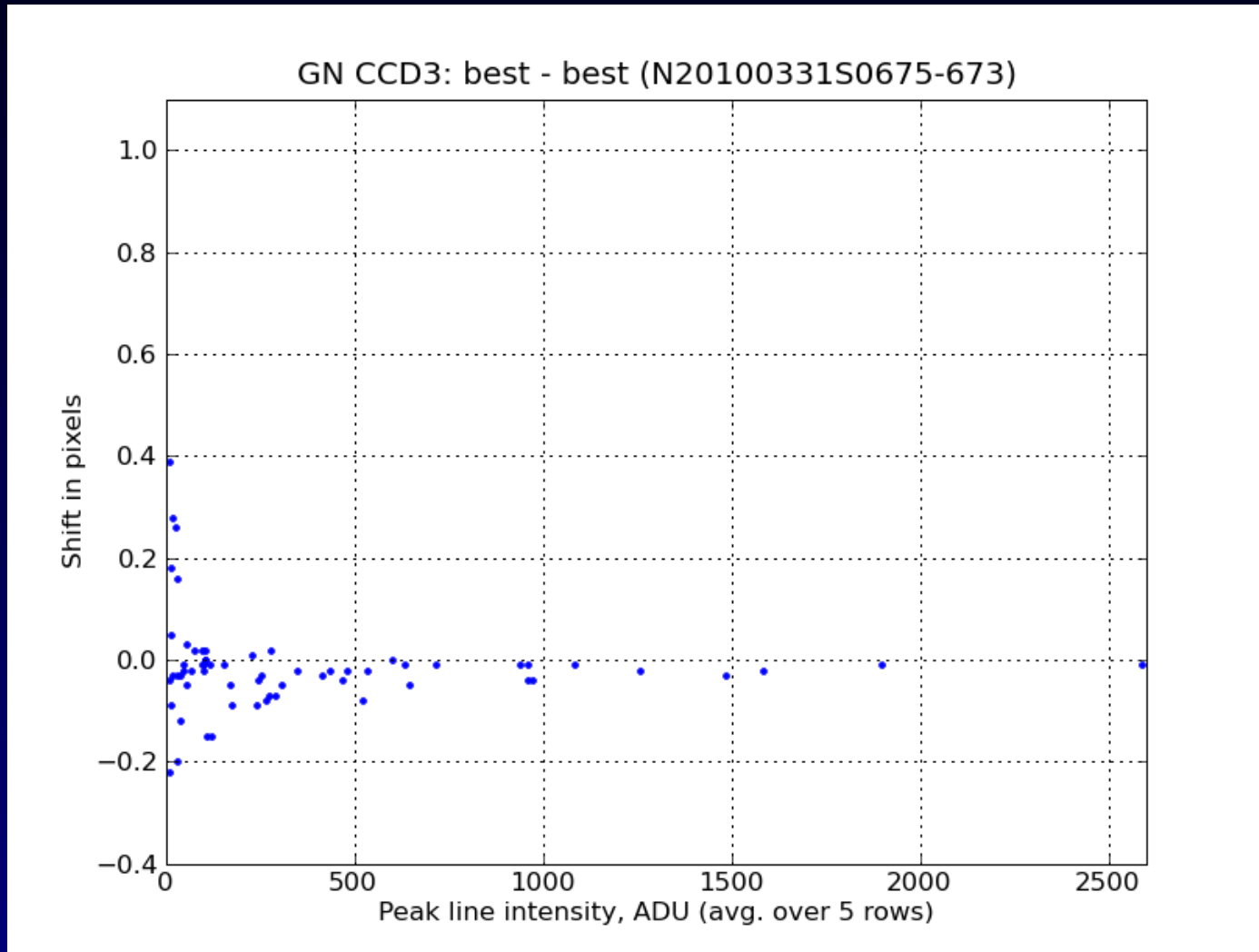
- What's wrong with the wavelength calibration?
 - (After *much* investigation) Nothing!
 - Must be the data!
- Eventually figured out (following some suggestions from my former Ph.D. mentor) that it's a problem with Charge Transfer Efficiency
 - As the CCD is clocked out, some charge trails on the detector
 - Alters line centroids with respect to detector co-ordinates!
 - The GMOS CCDs are clocked out in different directions, so the effect is reversed between the 2 slits.

Kinematic discontinuities

- Experiment – arc lamp exposures with the telescope stationary:
 - 1 Read out each chip with its standard amplifier
 - 2 Take an identical exposure, reading out in the opposite direction with the backup amplifier
 - 3 Take another exposure with the standard amplifier to ensure nothing moved & characterize the intrinsic errors
 - 4 Compare line centroids

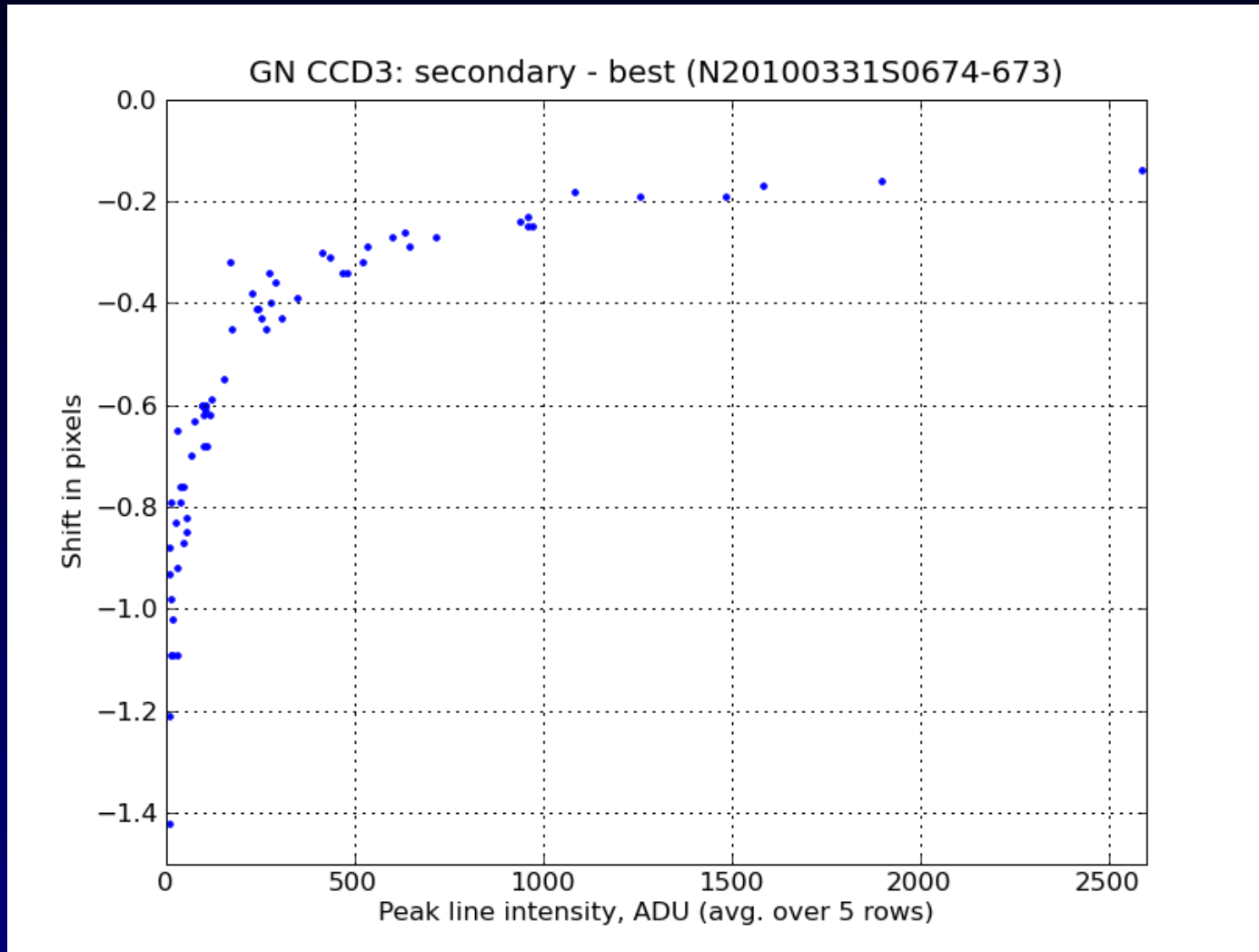
Kinematic discontinuities

- Difference in line centroids with intensity between control exposures:



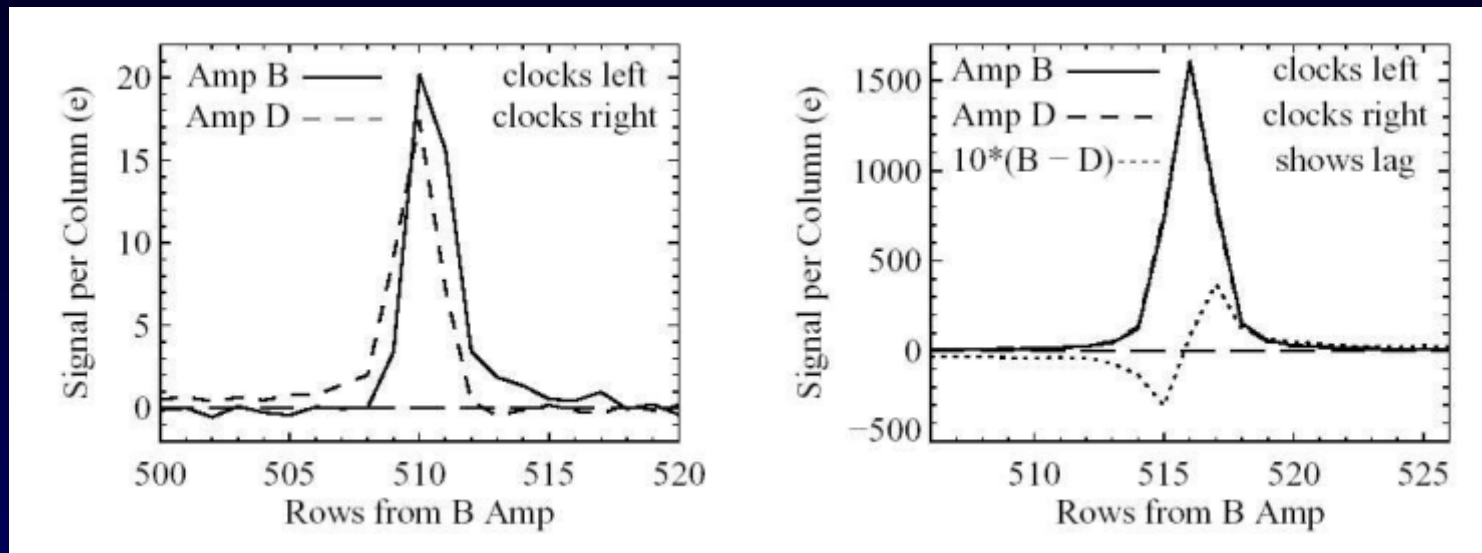
Kinematic discontinuities

- Secondary amplifier centroids minus best amplifier centroids:



Kinematic discontinuities

- Found a STIS paper (Goudfrooij et al., 2006) describing the same phenomenon:



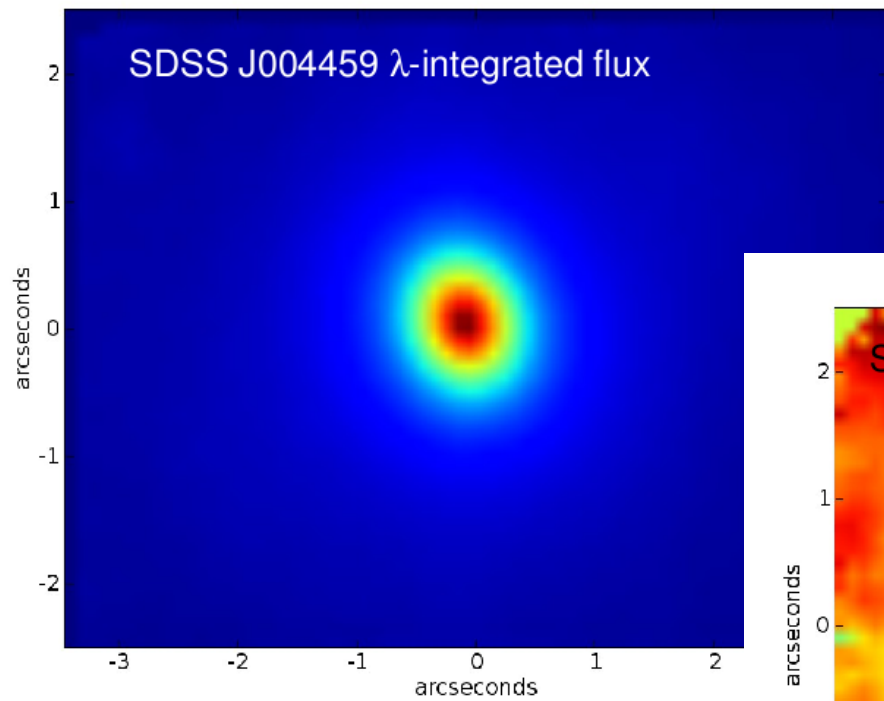
Kinematic discontinuities

- How to deal with the problem?
 - Wavelength calibration: pick out the brightest lines, as discussed earlier
 - these are almost unaffected by CTE and give a good solution
 - The transformed arc *looks* bad, but really it's correct!
 - Sky subtraction: treat each slit separately, as discussed earlier, since each one is slightly shifted with respect to the overall average sky spectrum
 - Science exposures: I'm still investigating the best solution
 - Could try to “deconvolve” the CTE shifts, but it would be a blind correction that's not straightforward to model
 - Instead focus on matching the systematics between science and template spectra – use multiple kinematic templates for different slits/intensities?
 - (New GMOS-N CCDs are coming...)

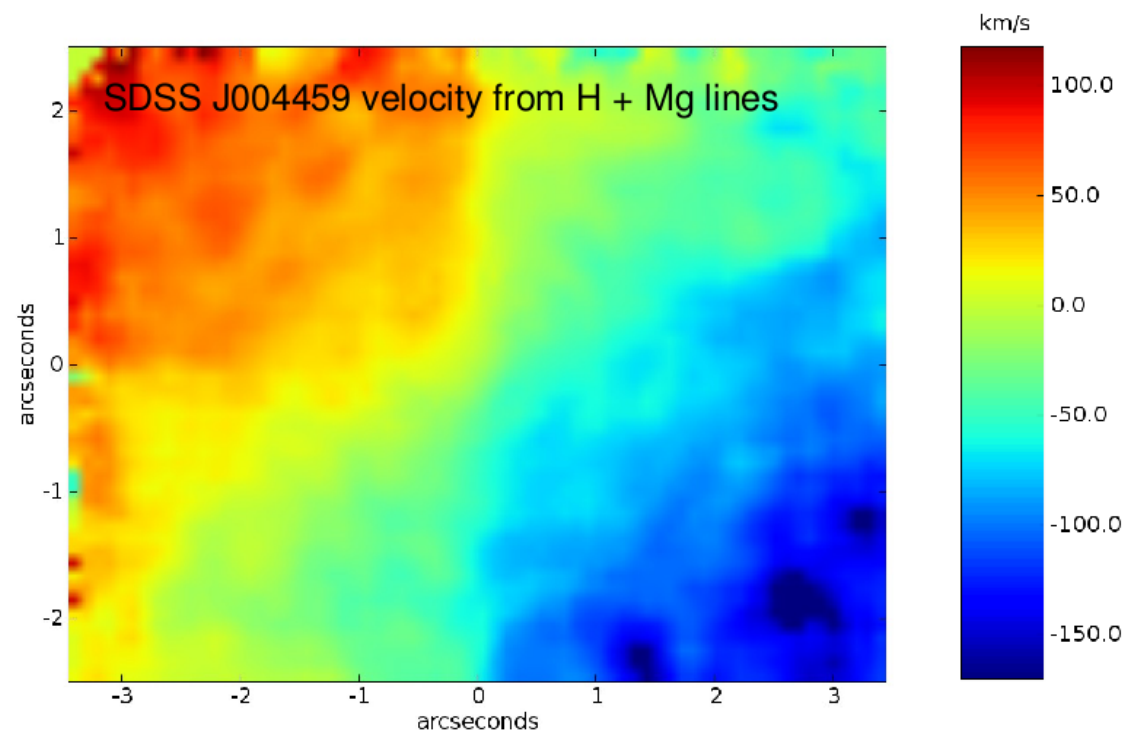
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Science project

- Finally getting back to the analysis again, but still early days.



To be continued...



Acknowledgements

- Bryan Miller: prototype improvements to the data reduction sequence
- Millie Maier: figures from her D.Phil. thesis & feedback on DR problems
- Jeremy Allington-Smith: suggestions that helped identify the CTE problem