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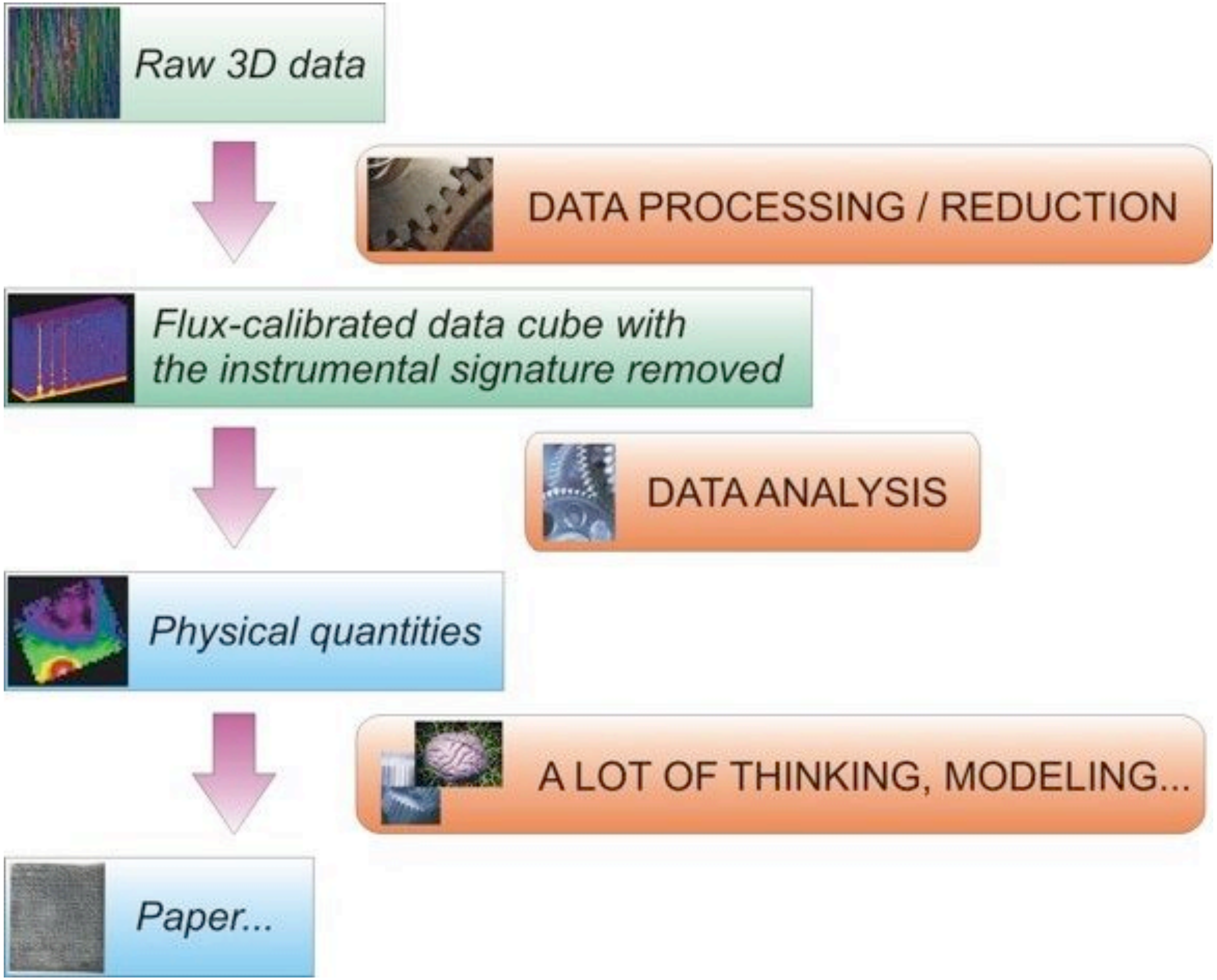
3. IFU data processing

(Thanks to James Turner & Richard McDermid)

- What is data reduction
- Signal to noise ratio
- Resampling/interpolation
- Data reduction
- IFU issues

From raw data to papers



What is Data Reduction?

- Removal of the observing system signature
- Key components:
  - ESTIMATES: Signal, noise
  - SAMPLING: Typically desire linear sampling in some coordinate system
  - CALIBRATIONS: specific frames used to make additive or multiplicative corrections
- End product has (hopefully significant) signal combined with random noise and (hopefully small) systematic errors

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Signal and Noise

$$S/N = \frac{\sqrt{n} \times Obj}{\sqrt{(Obj + Sky + RN^2 + DC)}}$$

Number of Exposures

Flux from Object

Flux from Sky

Read Noise

Dark Current

Noise

- Noise from the instrument
  - Detector noise
    - ✓ Read-out noise, shot noise from the dark current
  - Noise introduced during the data processing
    - ✓ E.g., due to the finite S/N of calibration exposures

- Noise from the undesired backgrounds
  - Shot noise from the backgrounds will remain even after a perfect subtraction of the undesired background

- Shot noise from the signal itself

- S/N of a dataset = key element for the analysis
  How real/robust are features you will detect / use ?

Noise propagation

- Keep track of noise propagation
- Required for any optimal stacking, binning, etc
- Published measurement should include error bars…
  - Keeping track of noise along the analysis
  - Easy to say, hard to do
  - Covariance ?
  - Monte Carlo

- ➔ Euro3D data cube to store this information together with your data

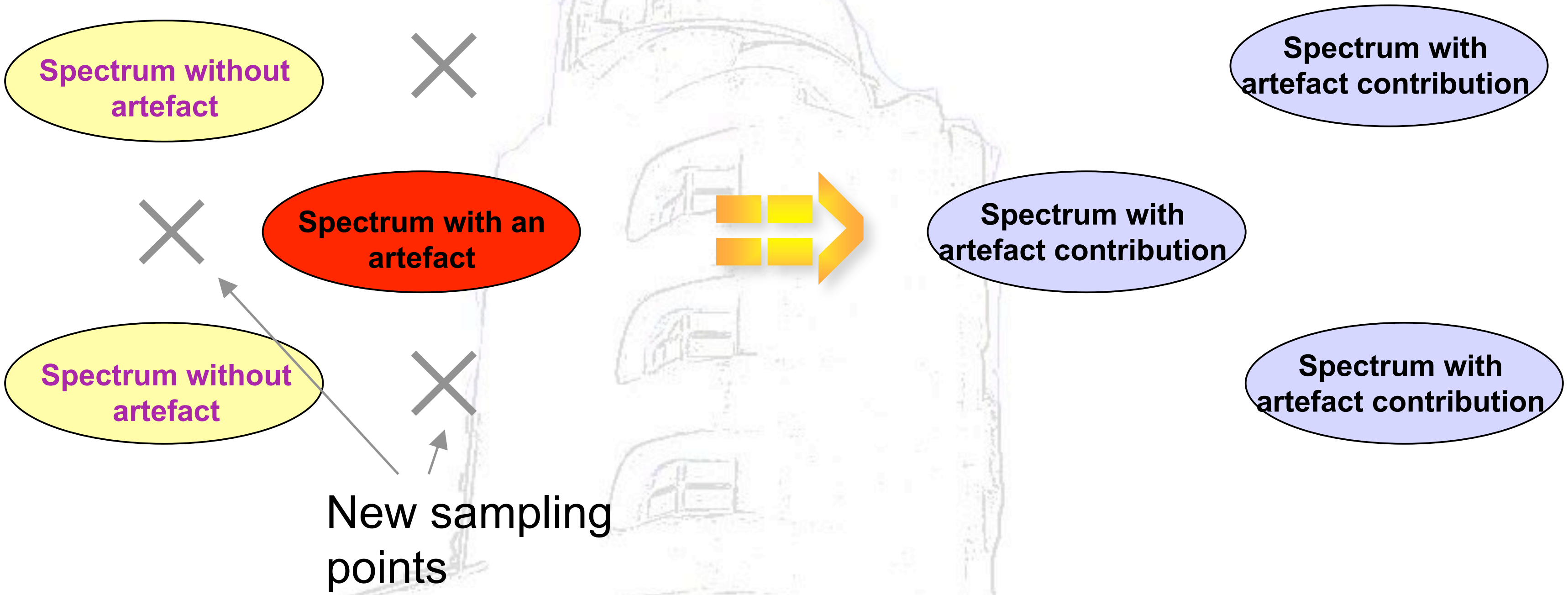
Resampling

- **Resampling a data set is seen by many as EVIL !**
  - Usually not much choice in the spectral direction :
    - most datacubes are resampled spectrally during the wavelength calibration

  - Spatial resampling can usually be avoided (and usually is)

- **All this is due to the problem of**
  - Spreading the artifacts over several spaxels
  - Following the noise pattern (correlation)
    - The spectra are not independent anymore
    - Summing /averaging a resampled dataset: lower gain?

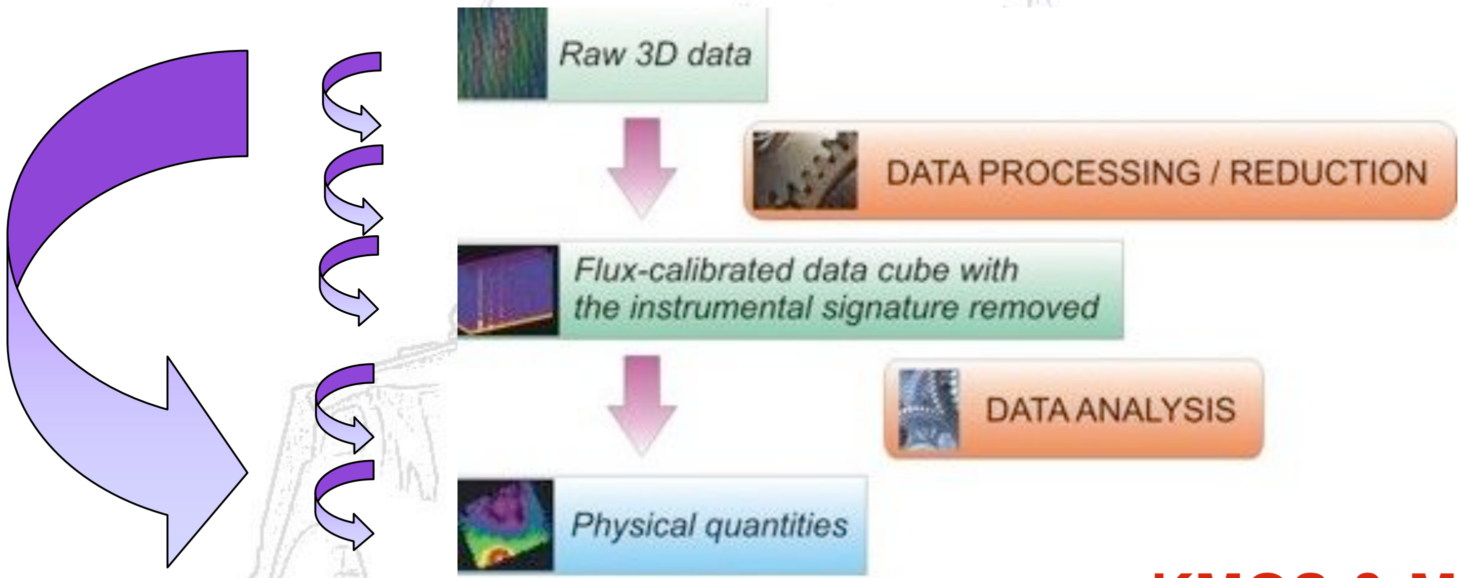
Propagation of artefacts



- Artefact has been:
  - spread out - more data loss
  - attenuated - less likely to be identified

An all-in one solution ?

- Minimise the number of steps including a resampling
- Associate data analysis tools with data reduction software
  - The “ultimate” solution : to keep working with the detector pixels
  - ➔ requires a lot of bookkeeping



KMOS & MUSE

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Data reduction

- Each ESO instrument has a dedicated data reduction software package (‘pipeline’)
- But piplines are often ‘blackboxes’
- IFU data is complex and voluminous
- so, ...

Datacube reduction can be tricky…

Data reduction

- **To get the most out of an IFU instrument:**
- Need to understand data reduction steps
- Have flexible tools to interact/modify pipelines
- ➔ ESO Reflex (more on Friday)
- Understand the details (‘nuts and bolts’) of an IFU

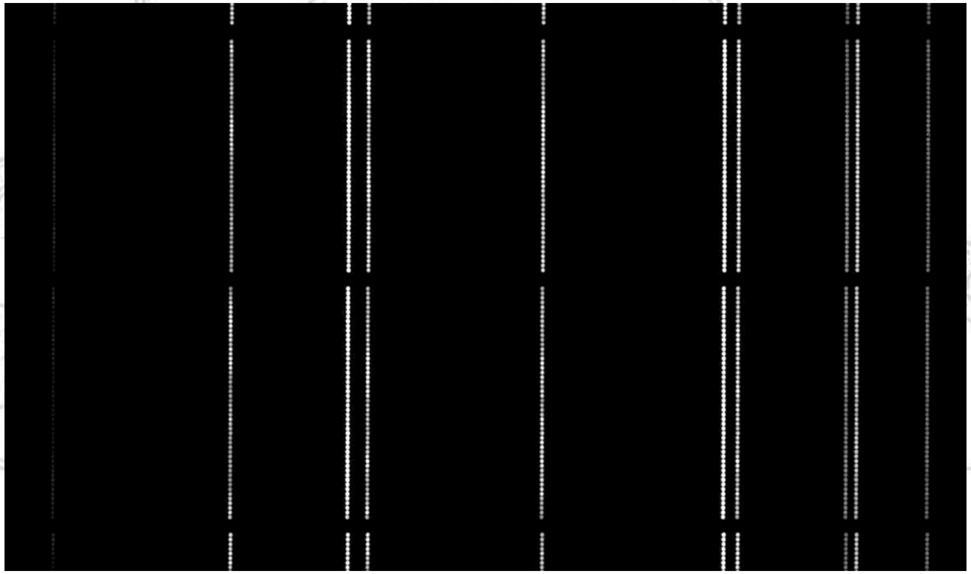
Reduction steps

- Wavelength calibrations
- Spectral flat-fielding
- Fringing
- Spatial flat-fielding
- Spatial calibration
- Sky subtraction
- Telluric absorption
- Flux calibrations
- Cosmic rays

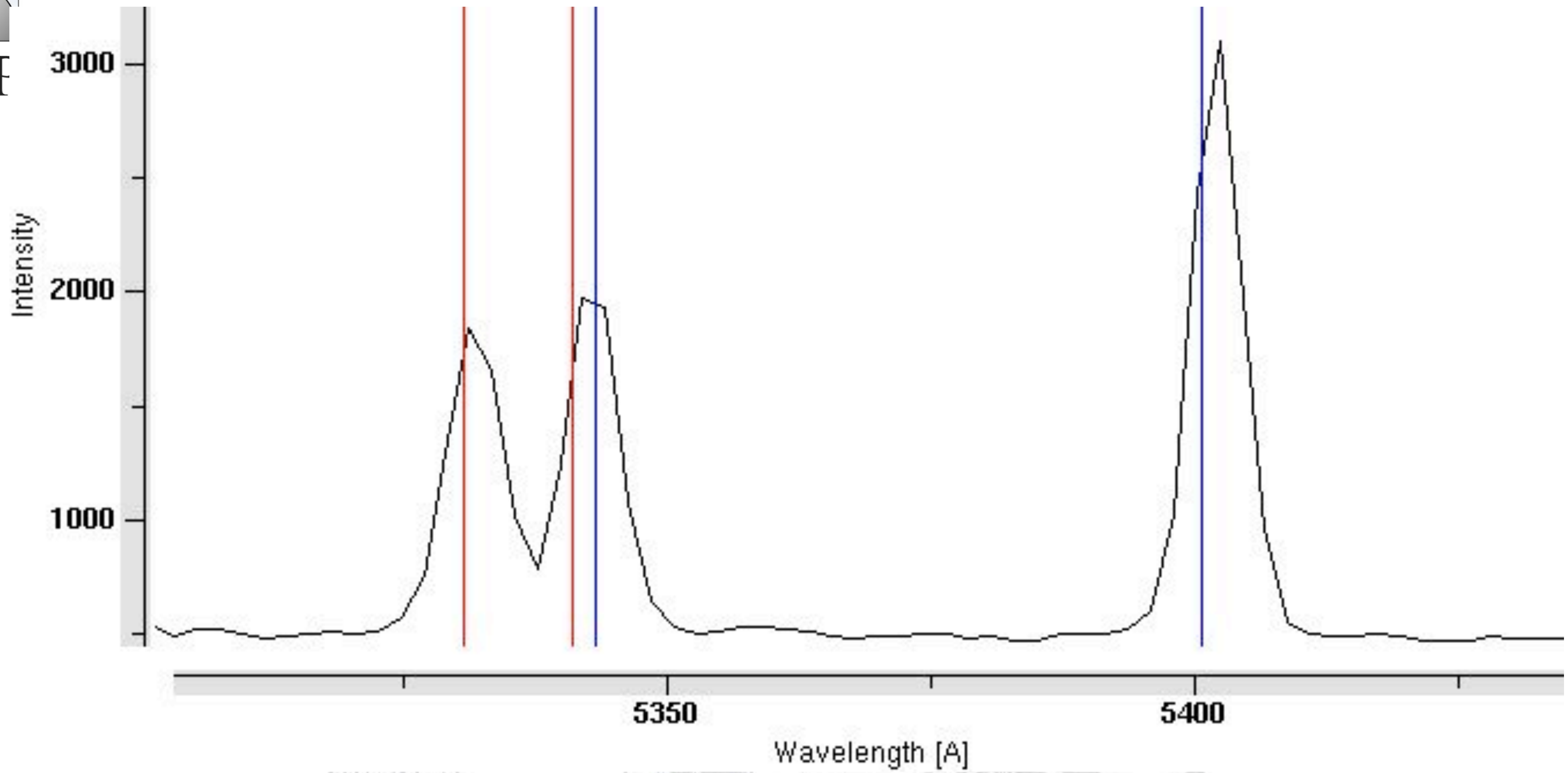
Wavelength Calibration

- What wavelengths fall on which pixels?
- How can we re-sample the data to have linear wavelength axis?

  ⇒ Find dispersion function: relationship between your pixels and absolute wavelength



Wavelength Calibration



- Compare reference wavelengths with measured arc-line centroids
- Blended and unresolved lines can create centroiding errors

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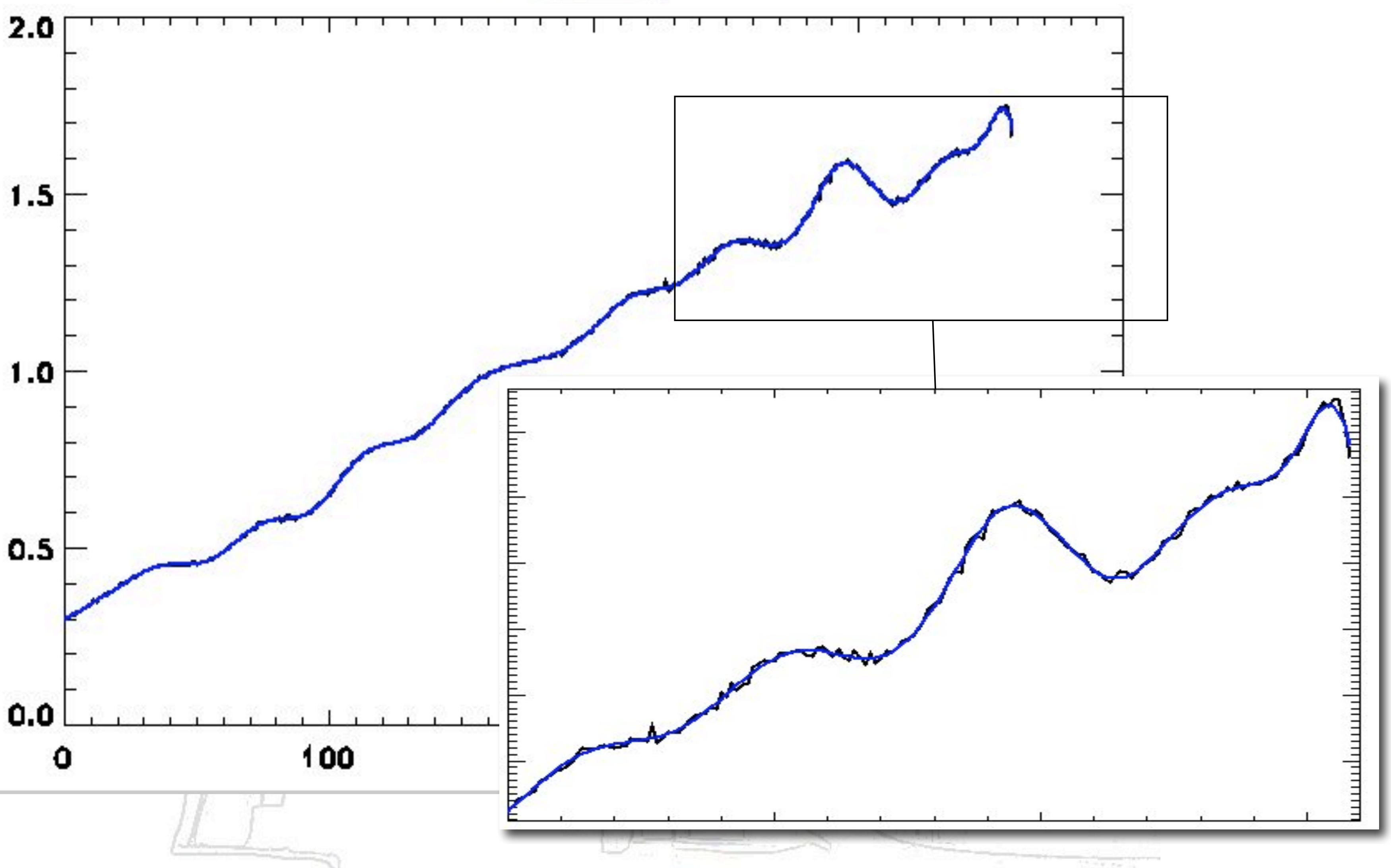
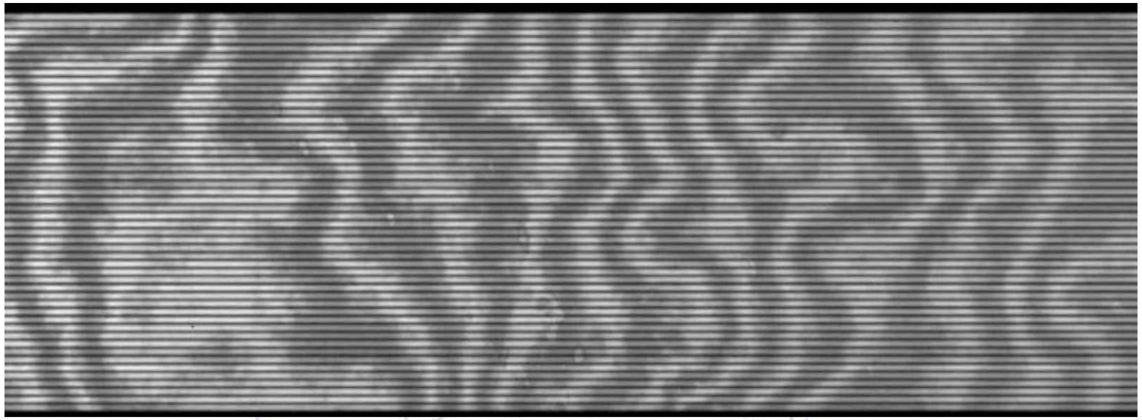
Spectral Flat-Fielding

- Instrument introduces a number of wavelength-dependent attenuations:
  - – CCD response, filter transmission, AR coatings, grating response, fringing…
- Observe a spectrally ‘flat’ source (black body) and either:
  1. Fit smooth function to mimic BB, then divide by actual flat data
     - Introduces noise and artefacts
     - Corrects for pixel response
  2. Fit higher-order function to transmission wiggles, and use the fit to ‘flatten’ the data
     - Noise-free (but fit has systematics)
     - no pixel-to-pixel correction
- Due to initial extraction process and flexure for fibre & lens IFU, option 2 is common

Spectral Flat-Fielding

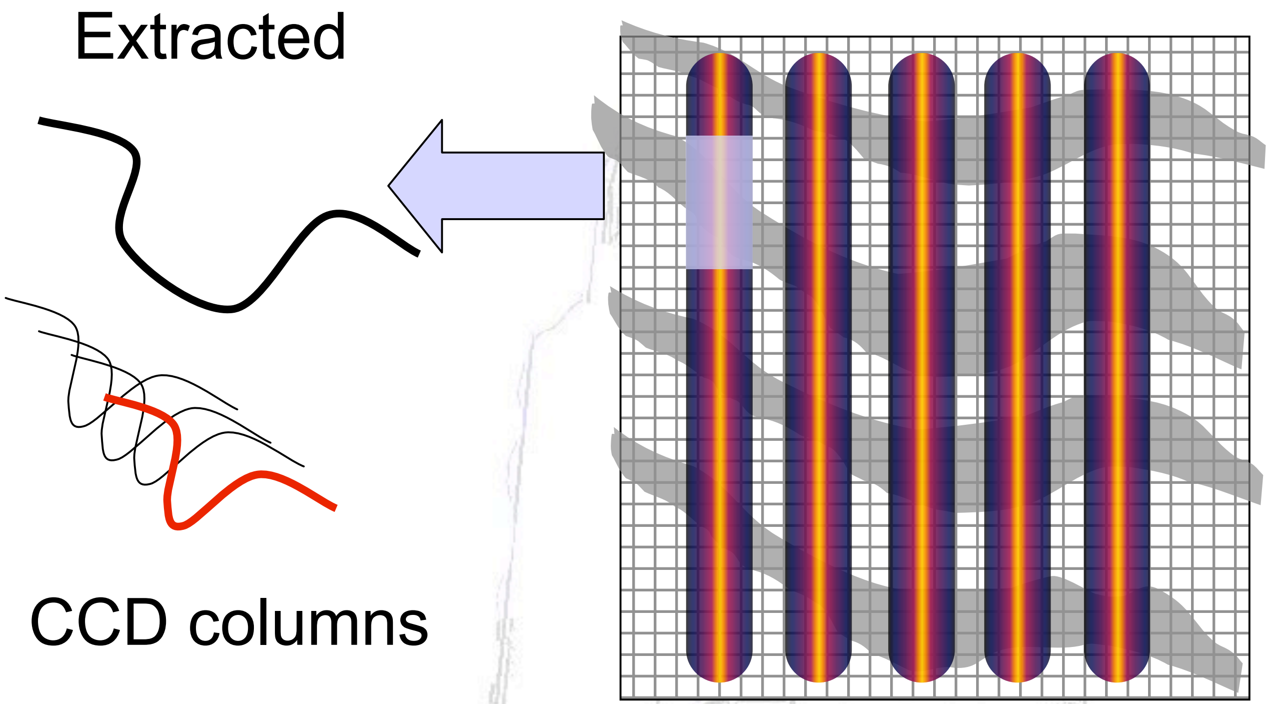




Detector fringing in fibre spectra - continuum lamp

- Fringing occurs at the CCD when the light wavelength is comparable to the substrate thickness
- An interference pattern is set up, depending on λ and CCD position
- Multiplicative effect for spectroscopy (additive in imaging, related to monochromatic sky emission)
- Correction requires homogeneous illumination and stability

Fringing



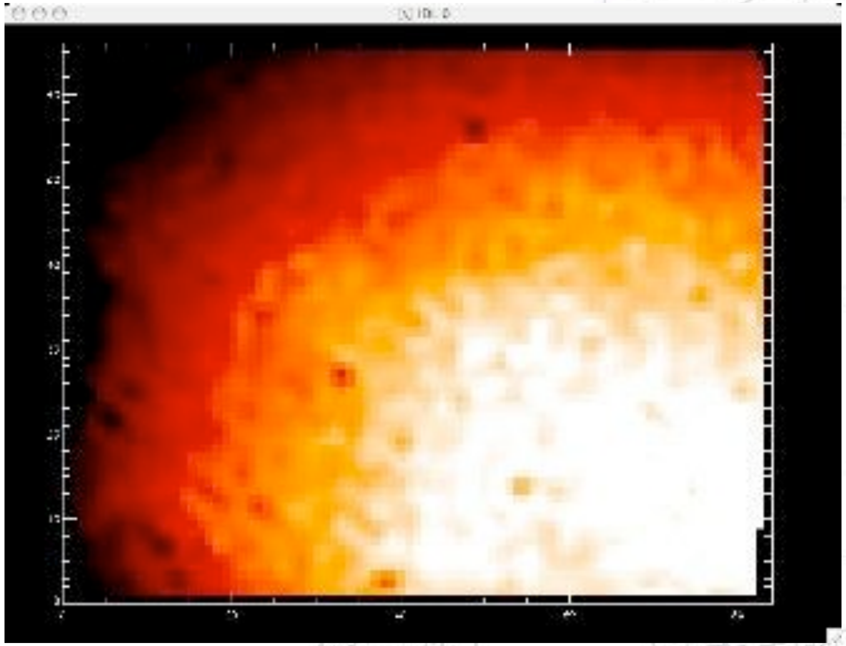
- After extraction, fringing is broadened ⇒ correct before
- Some regions poorly illuminated ⇒ large uncertainties
- Flexure changes illumination + fringe pattern ⇒ unstable

Spatial Flat-Fielding

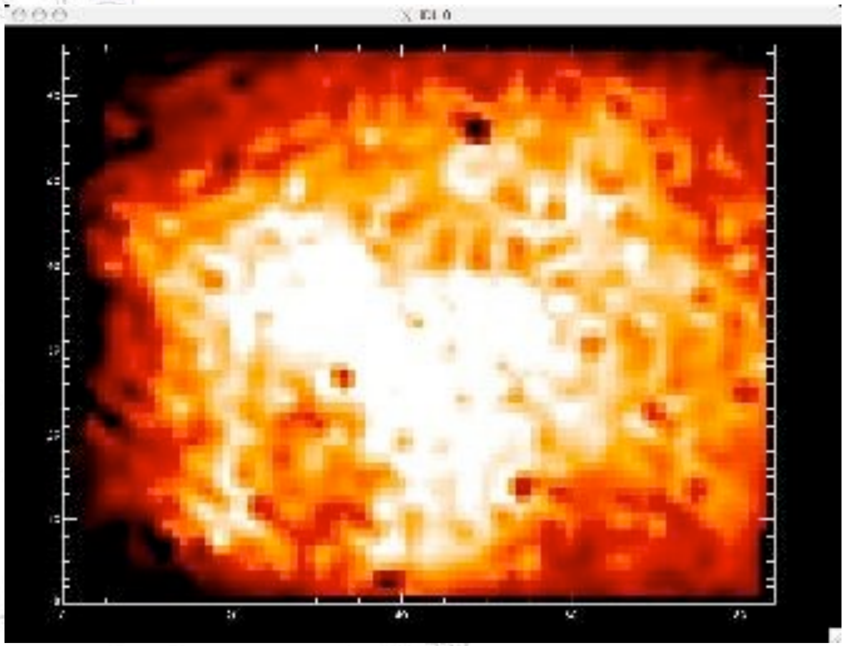
- Like an imager, IFUs need 2D spatial flat field
- Optical train is much more complex than an imager. Vignetting typically due to optics, pupil masks, etc.
- Typically spatial resolution is too low to be very sensitive to e.g. dust particles
- Still need global illumination function
- Best to use integrated light from the sky rather than internal lamp

Spatial Flat-Fielding

Lamp



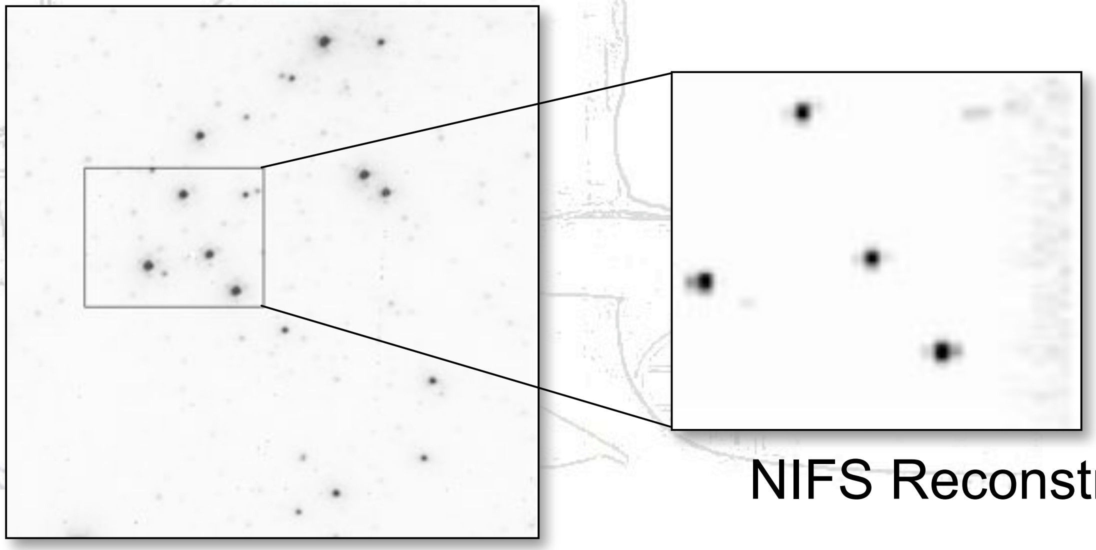
Sky



OASIS illumination

Spatial Calibration

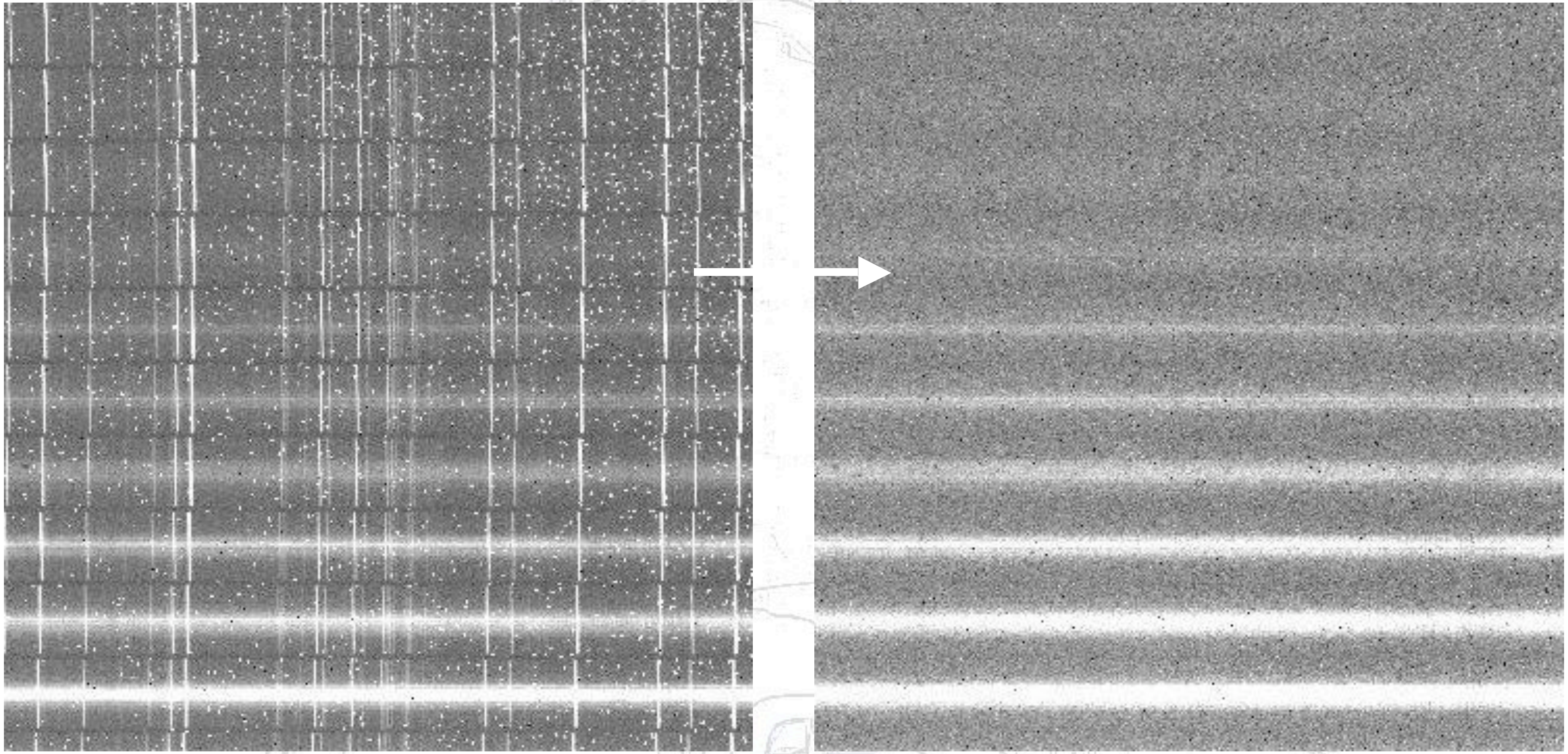
- IFUs have complex optics that may introduce non-negligible distortions in the spatial plane
- Important for astrometric applications - in practice, compromise between FoV and spatial sampling reduces the significance
- Lenslet-based instruments have spatial stage fixed by lens array - usually well known
- Slicer-based instruments more prone to flexure, esp. along the slit - needs calibrated
- Very important for large-format slicers, like MUSE



Reference image
(NIRI, Gemini North)

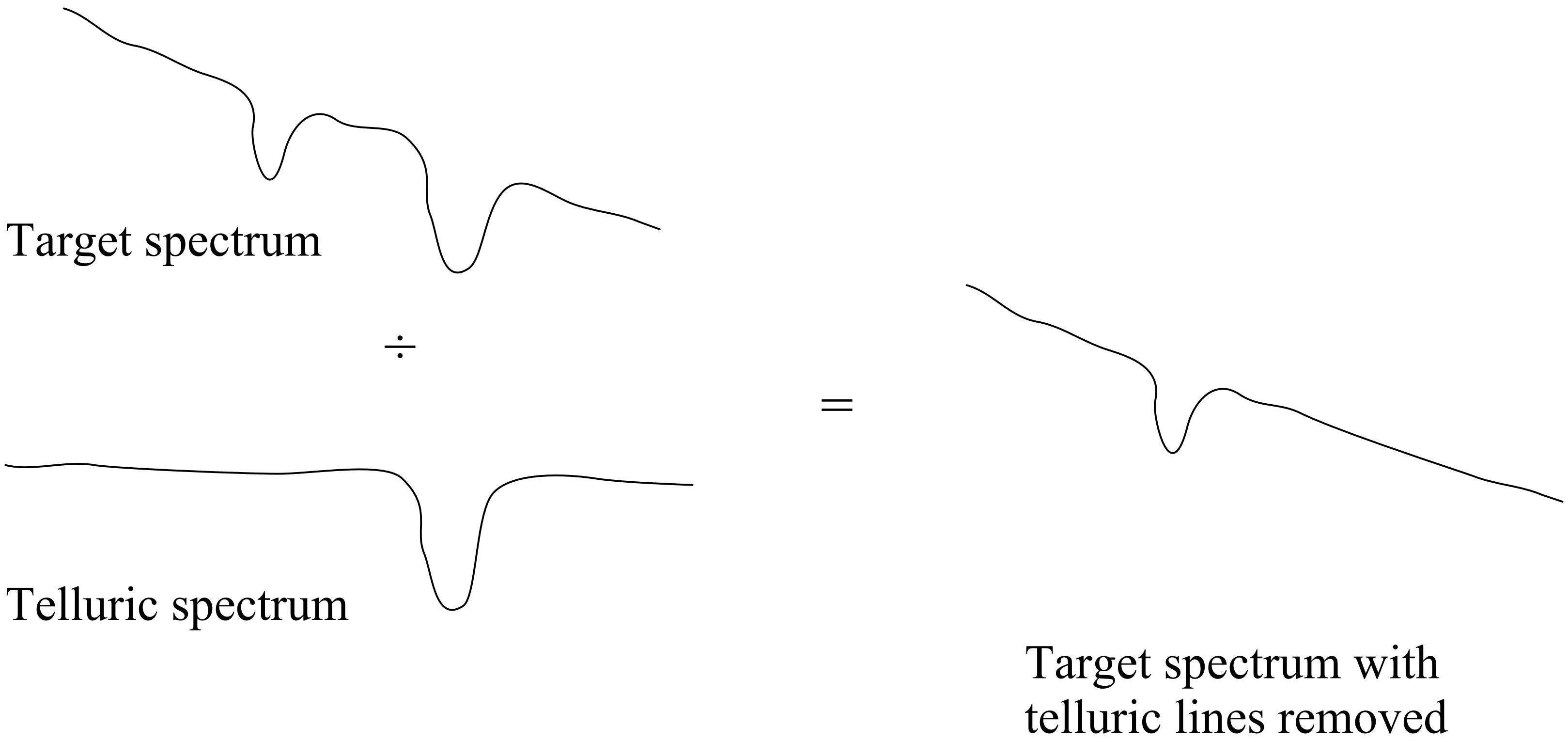
NIFS Reconstructed

Sky subtraction



Telluric absorption correction

- Varying (absorbing) atmospheric lines
- Very strong in the NIR, but optical features exist
- Correct using either:
  - a BB-like spectrum (featureless)
  - Or a sun-like spectrum (G star)
- Requires a good match of airmass, and conditions



Flux Calibration

- Requires a known reference: e.g., a standard star
- Compare the calibrated spectral response of the reference object with a « reduced » spectrum

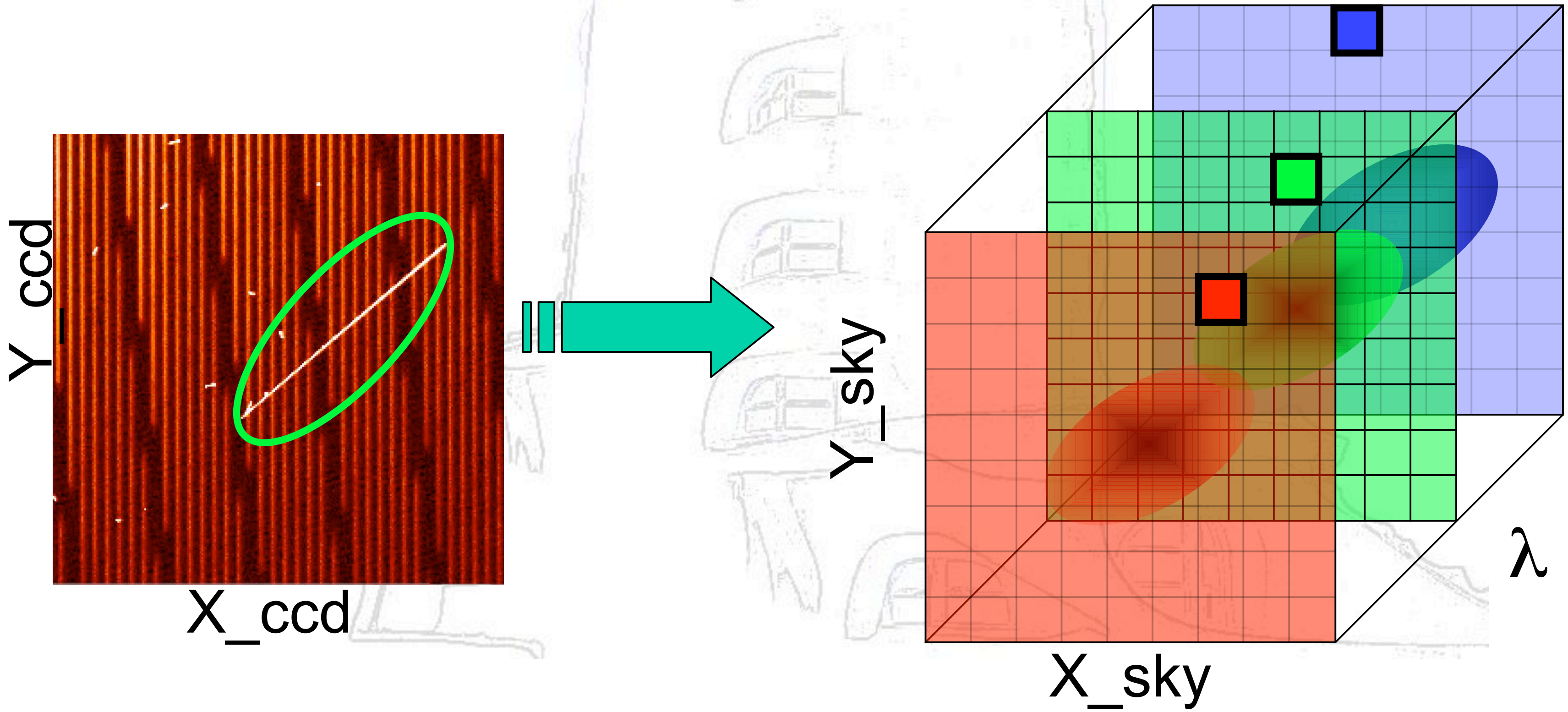
➔ This provides physical units : $W.m^{-2}.s^{-1}.A^{-1}$

- But: what is a photometric night?

- Beware of problems in standard star spectra:
  - Bad wavelength calibration
  - Different spectral resolutions
  - Varying sources!

Cosmic Rays

- Use the fact that CCD coordinates are decoupled from data-cube coordinates
- Cosmics have high contrast in image planes
- Real features follow smooth/PSF distribution
- But better to do before resampling



‘Un-mapping’ 2D to 3D

or building the datacube

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- Standard approach is to first ‘extract’ 2D spectra into 3D (x,y,λ) ‘data-cube’
- Then cubes are resampled to linearize the three dimensions
- Initial extraction can introduce an extra resampling step compared to long-slit
- In practice very difficult to retain the original sampling during extraction
- Also difficult to use assumption of smoothly-varying properties as when CCD and physical coordinates are both neighbouring

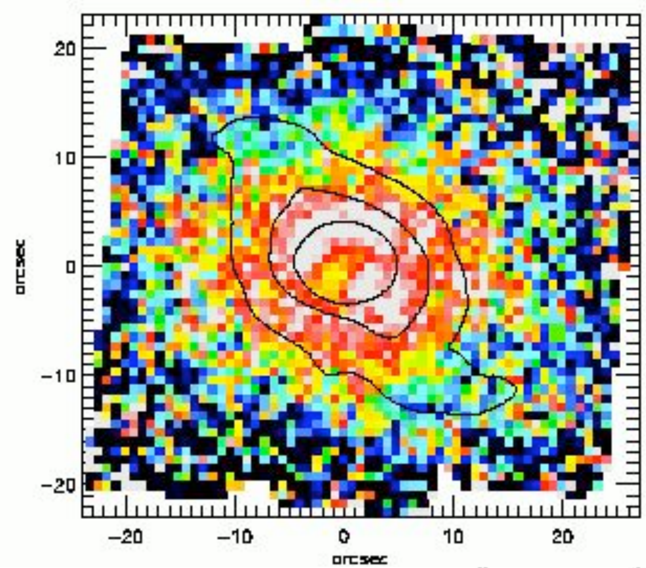
IFU specific issues

- Spatial binning
- Atmospheric refraction
- Mosaicing

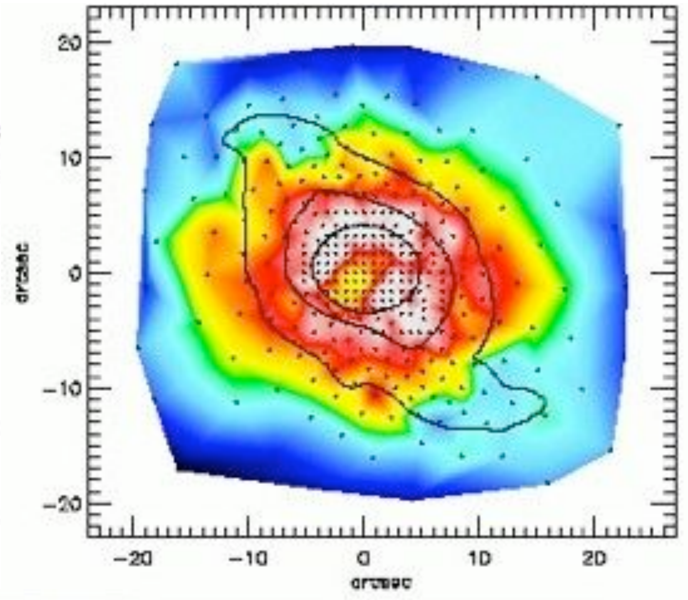
Spatial binning: voronoi tessellation

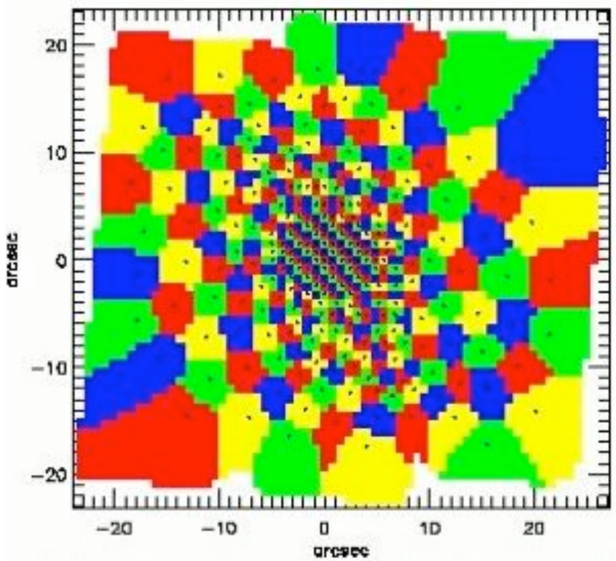
Cappellari & Copin 2003

Unbinned S/N map

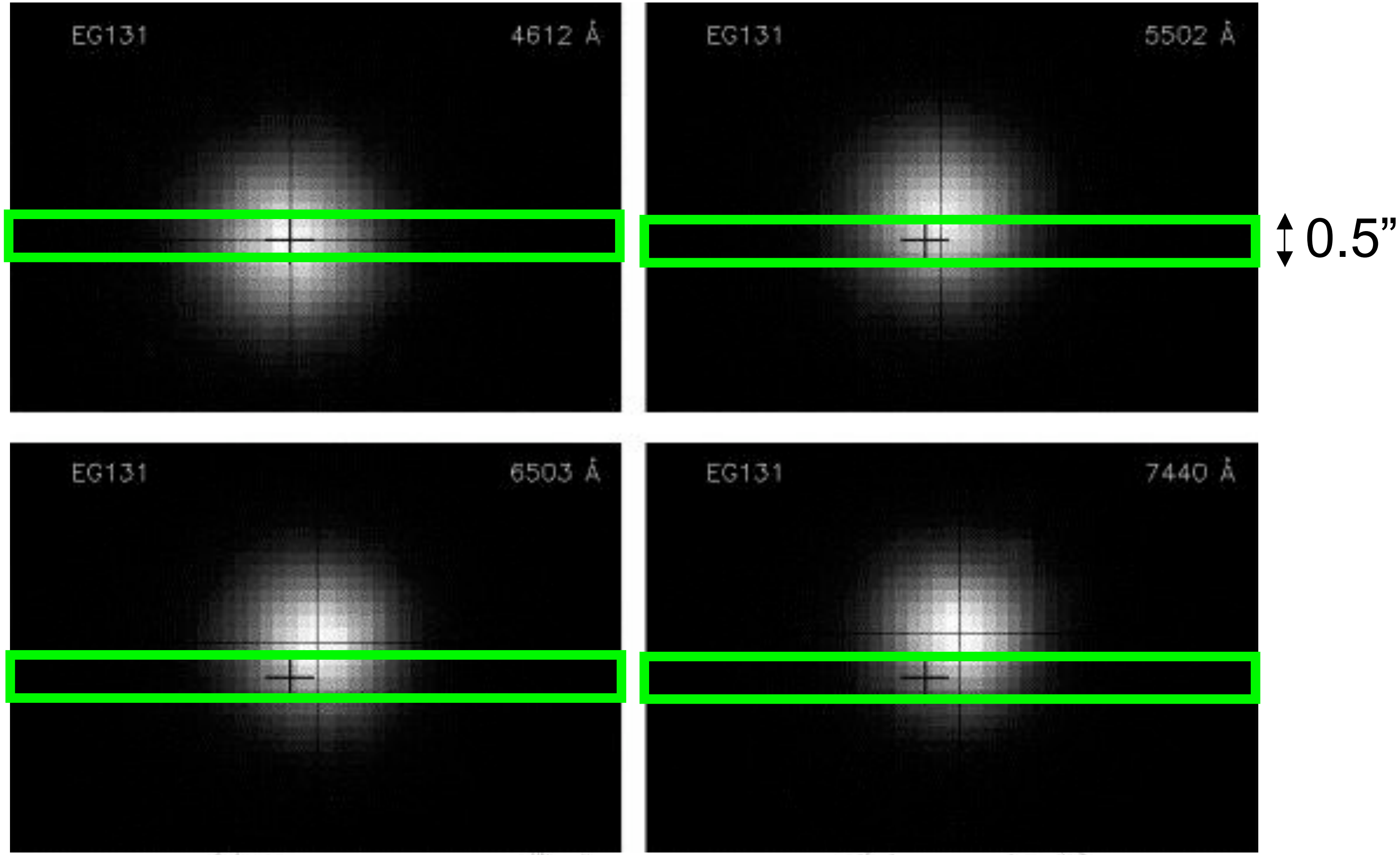


S/N map after binning





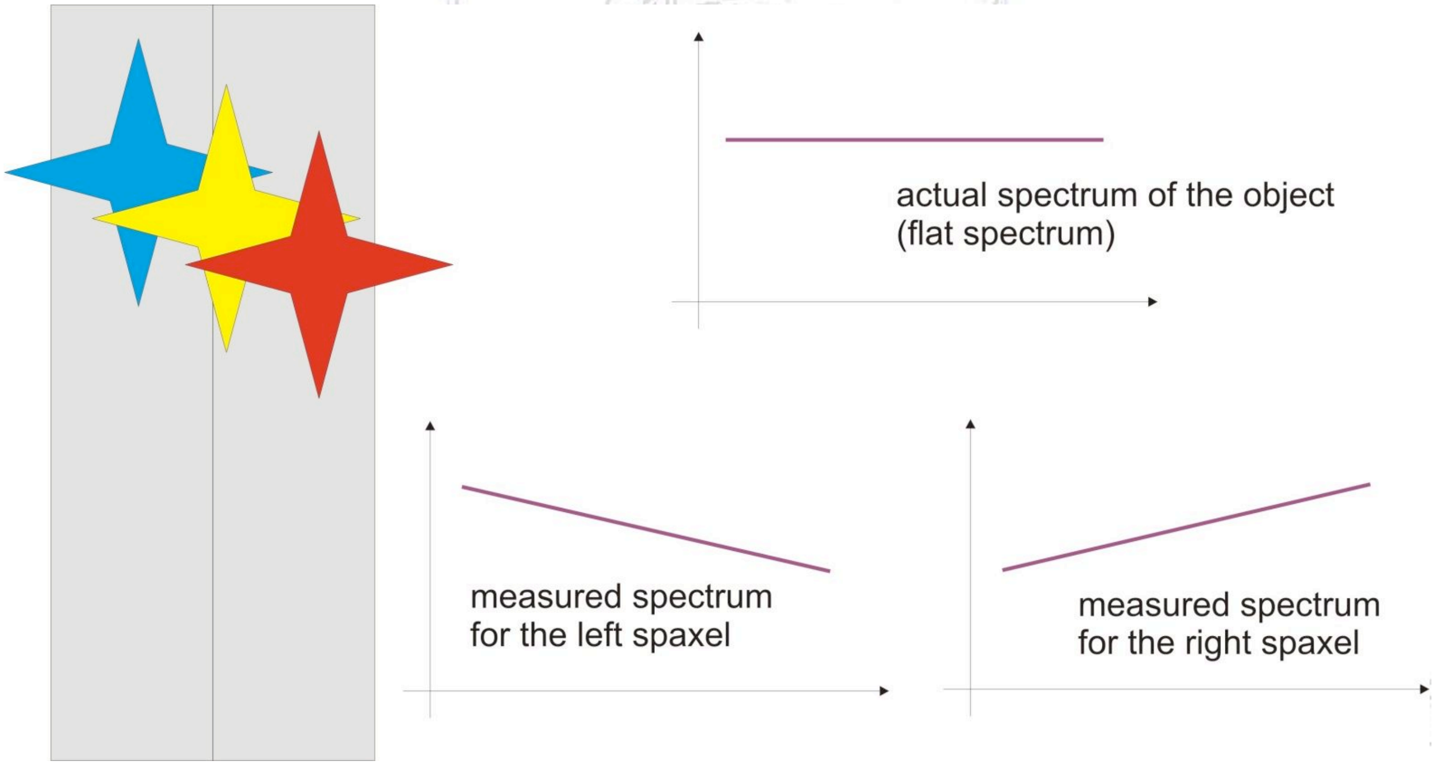
IFU Issues: Refraction



- Atmospheric refraction = image shifts as function of wavelength
- Shifts largest at blue wavelengths
- Can be corrected during reduction by shifting back each image plane

Atmospheric refraction

- Atmospheric refraction: images shift with wavelength
- ➔ ***Object moving out of the slit ?***
- IFS minimise the impact of this effect
- ➔ possible *software* correction (or ADC)

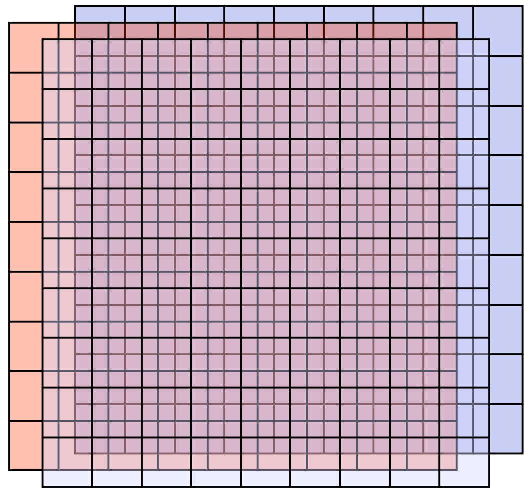


Emsellem et al. 1996; Arribas et al. 1999

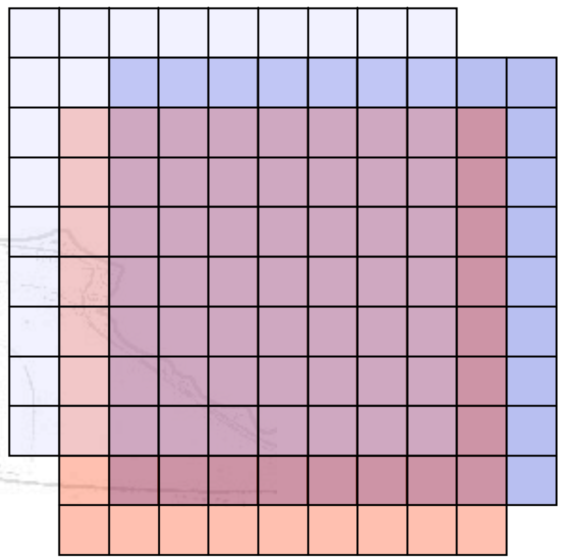
Co-Adding Data Cubes

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



Drizzling

- Technique used in imaging to improve the sampling of poorly sampled images
  - Heavily used for HST data
  - See e.g. Hook & Fruchter, 2000, ADASS #216 and references therein

- A natural extension to 3D spectroscopy
  - Handling of data cubes as stacks of monochromatic slices
  - *NO drizzling software adapted for data cubes*

Drizzling

Note that additional corrections like distortion correction and atmospheric refraction correction can be applied at the same time (and actually should be applied)

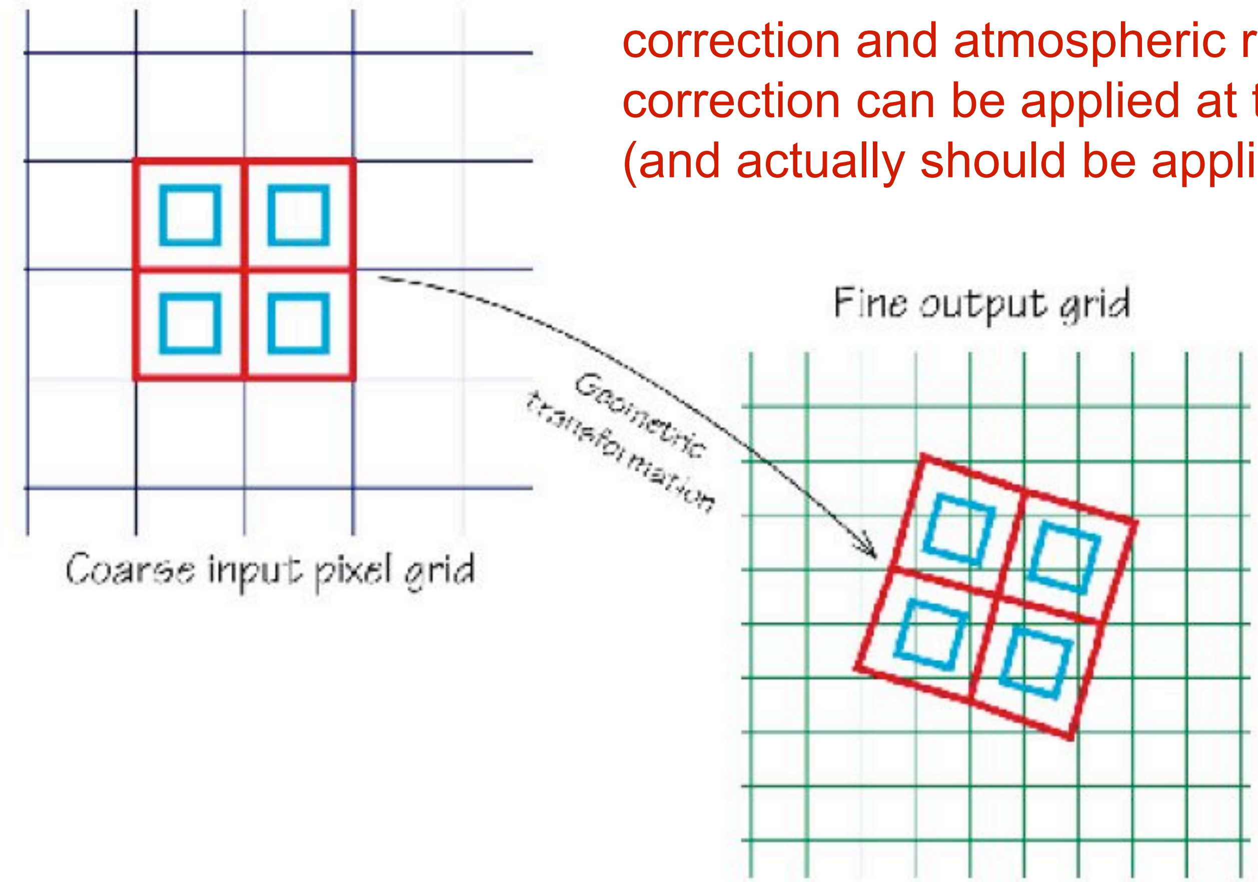


Figure 2: Illustration of how the drizzling method transforms an input pixel onto the selected output grid and showing the pixel shrinkage and general geometric distortion which can be included.

Summary

- A number of reduction stages are the same as or similar to those for other spectroscopic modes
- In particular, IFUs have special requirements for
  - Flat fielding
  - The details of locating and extracting spectra
  - Mapping the data from 2D to 3D

- Remember you can do imaging with IFS, as well as spectroscopy!