# Integral Field Spectrographs

## *A User's (?) view*

**Eric Emsellem**

*(CRAL - Lyon)*

# If you have to leave just now

- *Keep track of the noise pattern*
- *Characterise the instrument (and data reduction)*
- *Develop Software on realistic data:*
  - ***Instrument Numerical Model***
- *1 SINGLE (evolving) version for the data reduction software*
- *Develop (and diffuse!) tools to handle the data*
- *Allow CALIBRATION PROPOSALS*

***How to optimise the output of this workshop?***

# Integral Field Specifics?

- **IFS (VIMOS, FLAMES, SINFONI, …):**
  - like any spectrograph…

- **But:**
  - ➔ ***Adding the issues linked with both***
    ***Imagers & Spectrographs***

# Specifics – I:
# No real Standard (yet)

- No good way to deal with the datasets (*but Euro3D*)

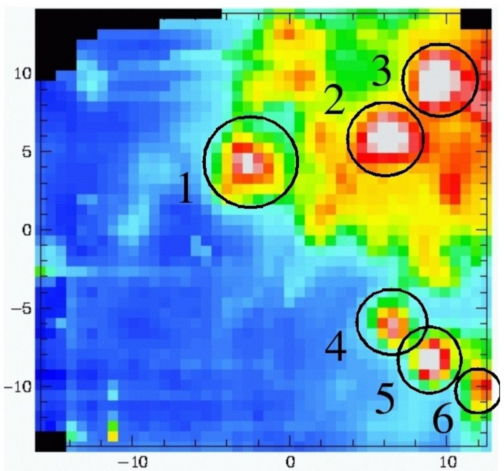
➔ Need for more tools to handle the data:
  - ✓ Slicing
  - ✓ Visualisation
  - ✓ Data mining

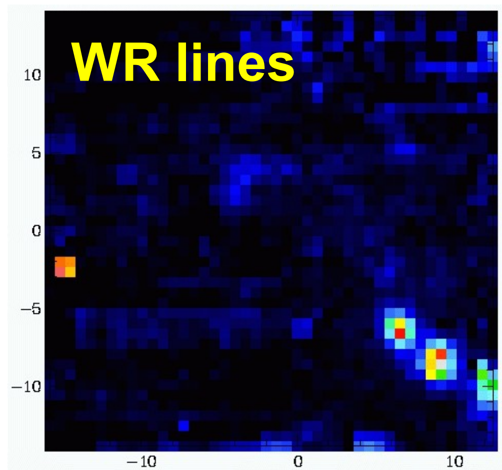
| Name | Year | N spatial | N spectral | N total |
|---|---|---|---|---|
| TIGER | 1987 | 572 | 270 | 154,440 |
| OASIS | 1997 | 1,200 | 360 | 432,000 |
| SAURON | 1999 | 1,577 | 540 | 851,580 |
| VIMOS | 2002 | 6,400 | 550 | 3,520,000 |
| MUSE | 2012 | 90,000 | 4,096 | 368,640,000 |

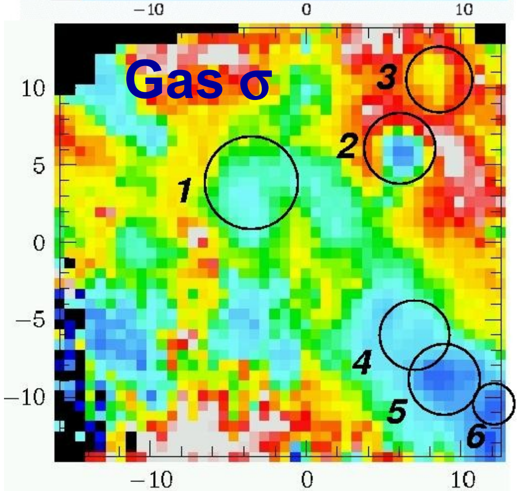
➔ *Expect blind processes*:
  - No way we can look at individual spectra
  - Accept (and evaluate robust) *errors*
  - Requires robust algorithms

# Specifics – II: Maps look GOOD

## VIMOS spectrography of clusters in merging systems

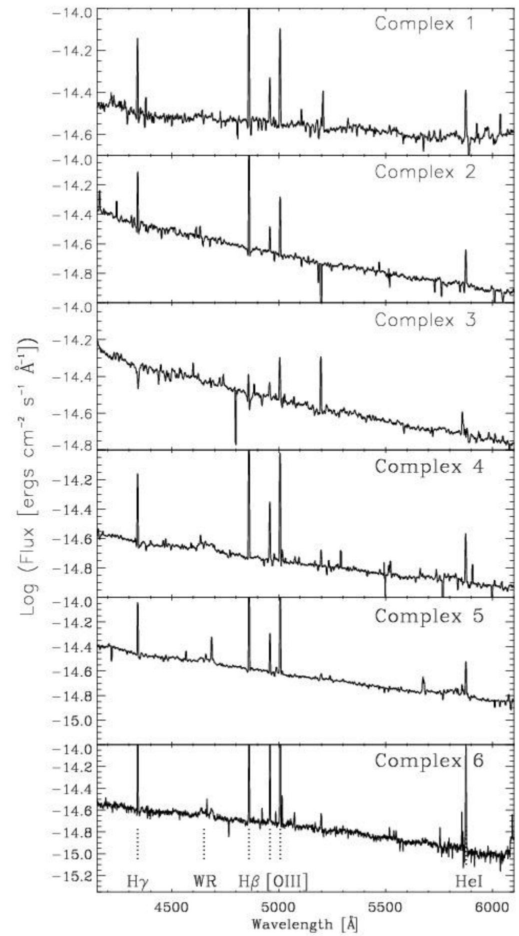


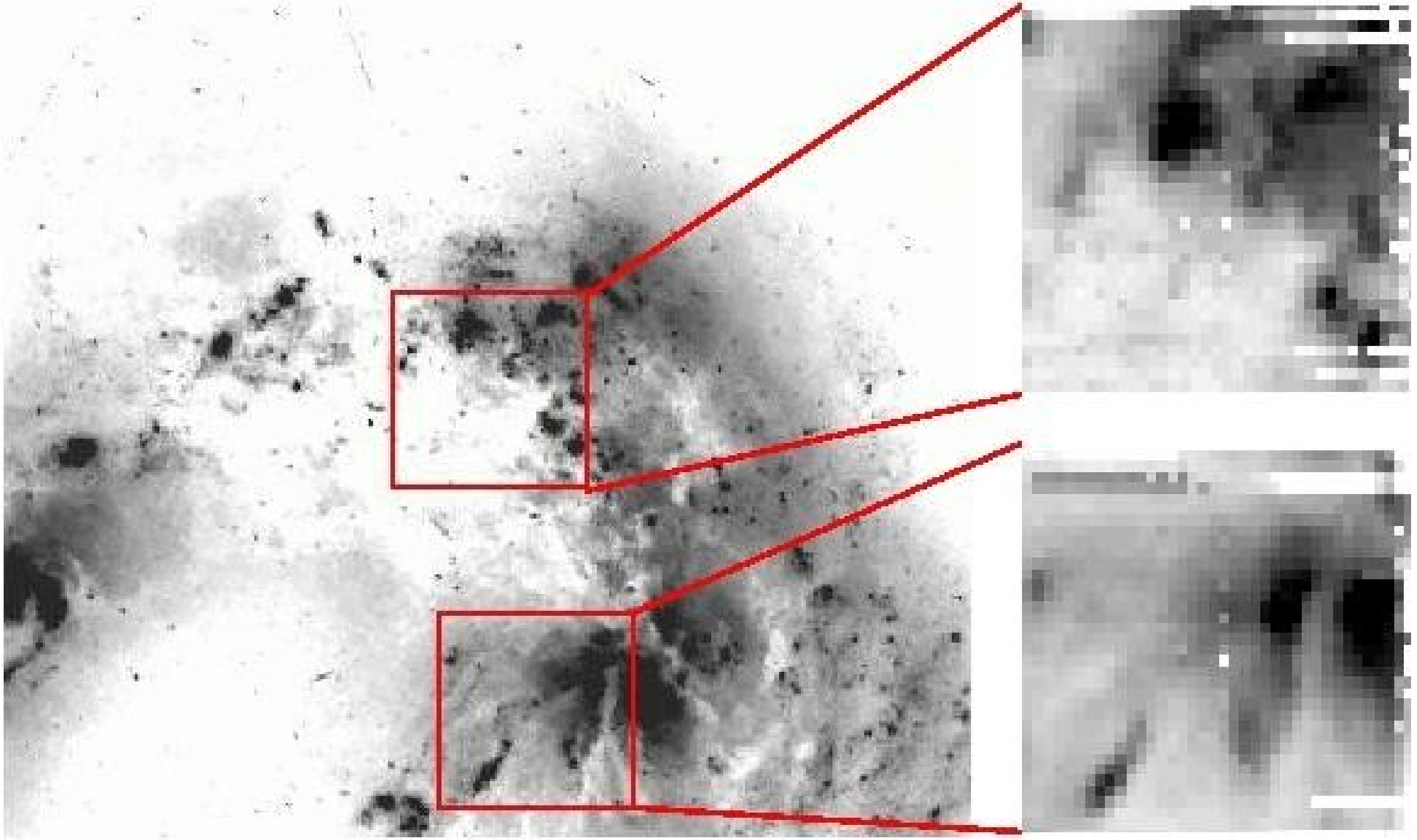




**The Antennae**

**Bastian et al. 2005**



# Specifics – II:
# Maps look GOOD



- How does this affect our science ?
- How do we deal with "errors" ?

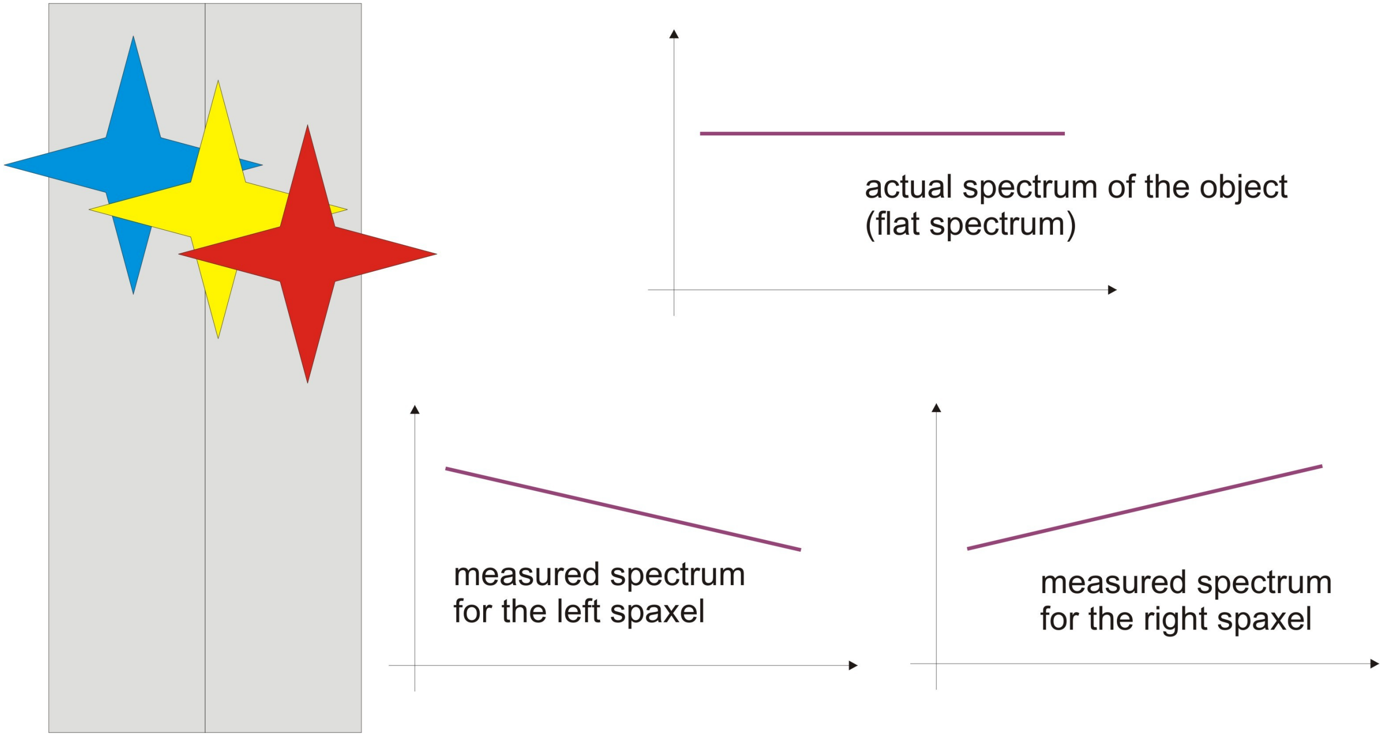
# Specifics – III: Spatial & Spectral

- **All spectrographs : mixed spectral + spatial information**
- **0D (aperture), 1D (long-slit) spectro :**
  - restricted access to the spatial information

- **Opening doors with 2D spectroscopy, e.g. :**
  - Seeing a posteriori evaluation & correction
  - Atmospheric diffraction
  - (Spatial) Test for artefacts

# Specifics – III: Spatial & Spectral

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

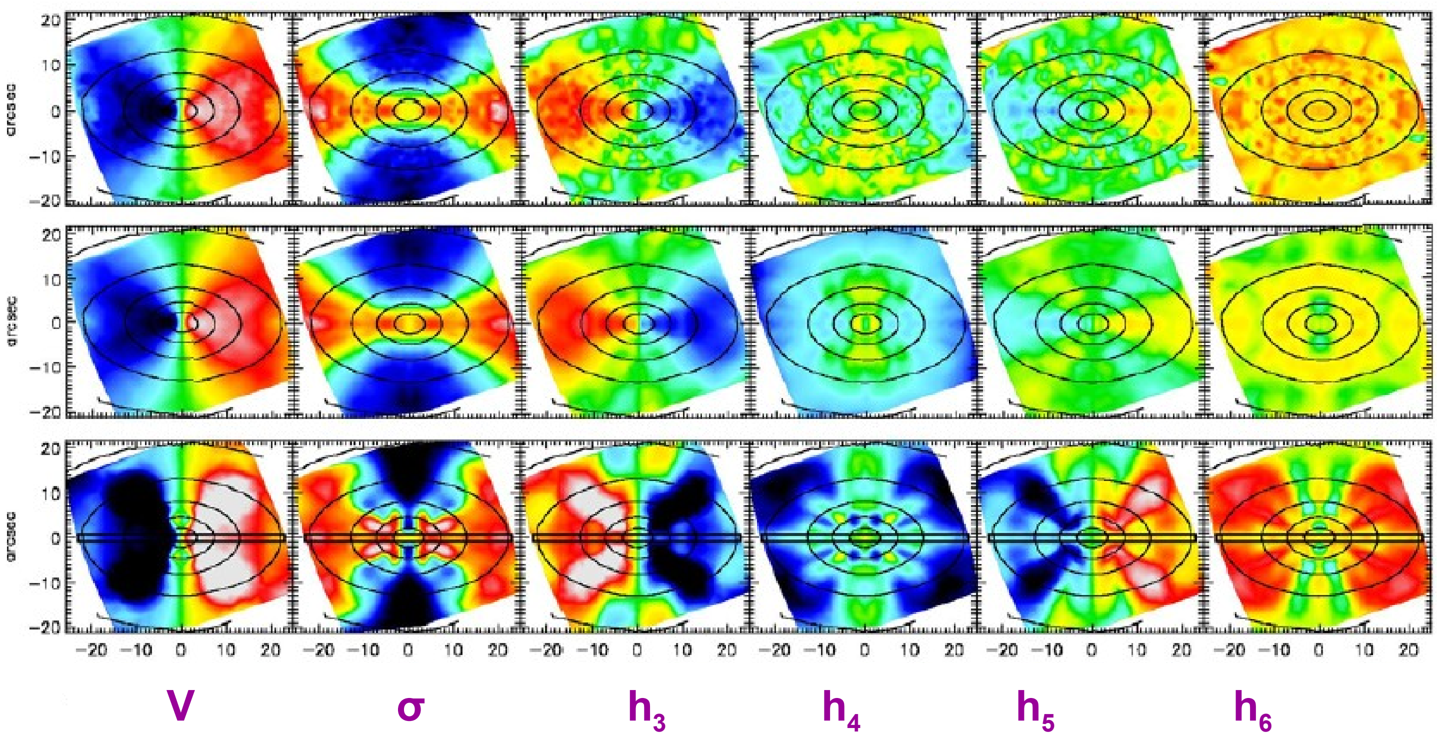



Emsellem et al. 1996; Arribas et al. 1999; *Theoretical predictions from e.g.* ***Fillipenko, 1982***

# Opening Pandora's box

- **Increasing the number of constraints :**
  - Robust global quantities, Modelling,
- Uncertainties in the modelling ≈ Errors from the data

➔ ***Need for a better data treatment***

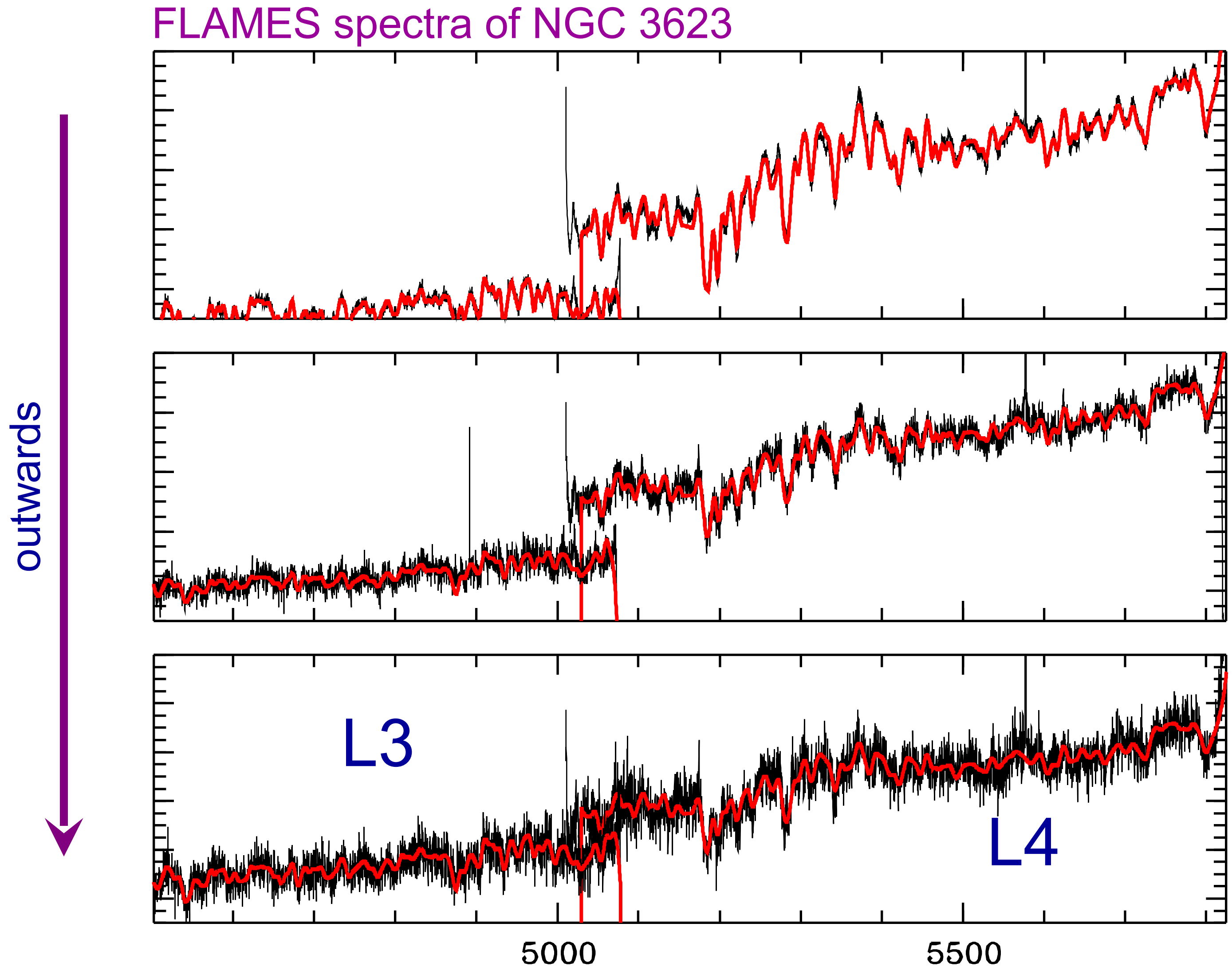



Cappellari & McDermid (2005)

# Pushing the limits

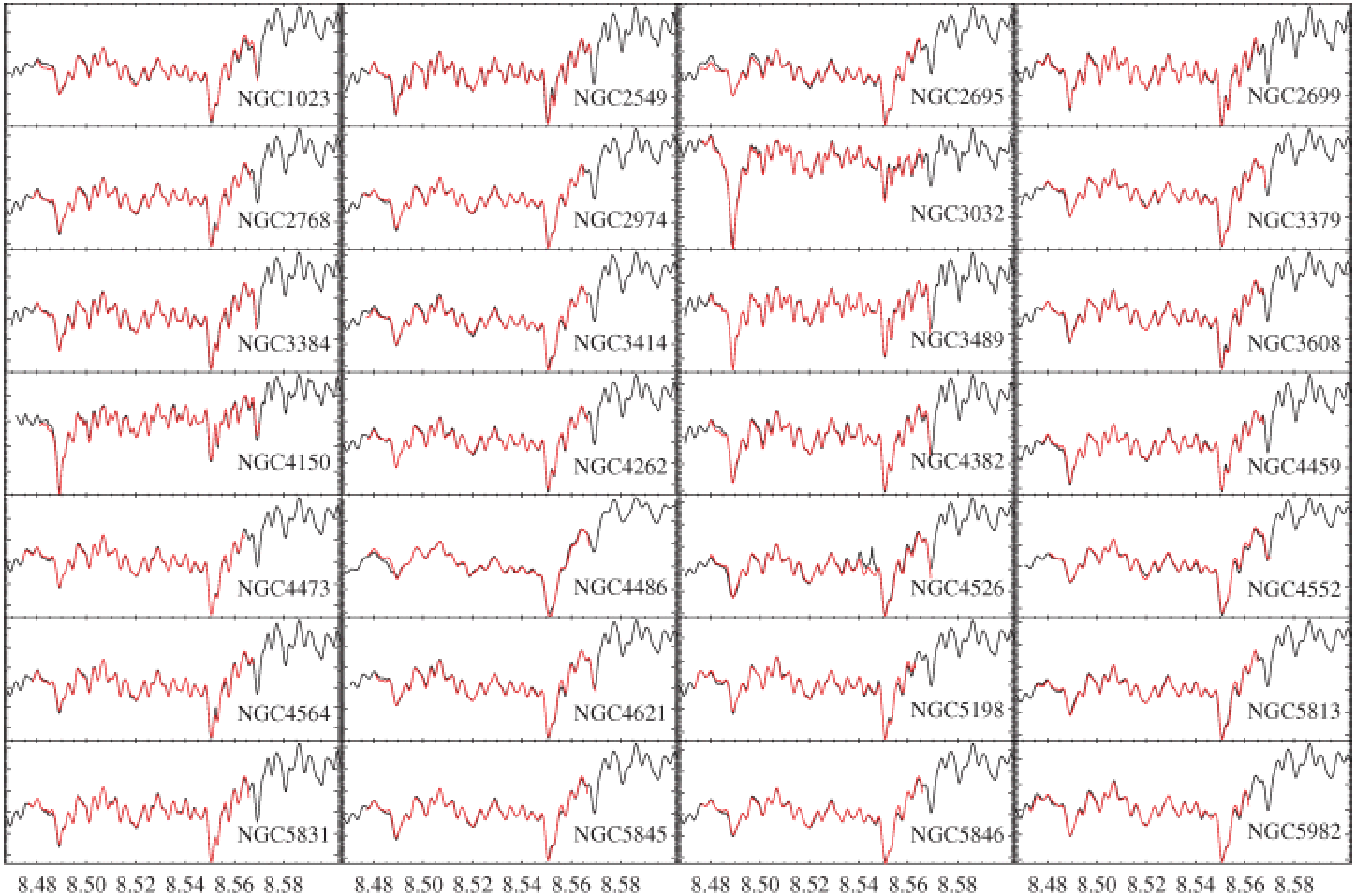
- Take advantage of the spatial mapping
  - *Comparing datasets*
  - *Super resolution*
  - *Connecting spatial domains (mosaicing)*
  - Deep fields (positioning, optimisation): MUSE
  - Spectrophotometry !
  - Adaptive Optics (& LGS)

# Pushing the limits - 1
# Connecting spectral domains



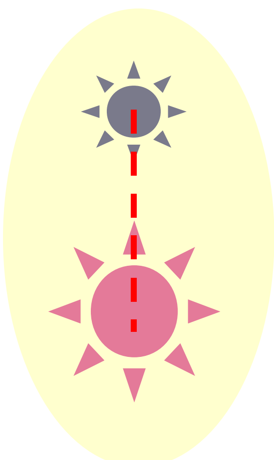
# Pushing the limits – 1
# Associating datasets

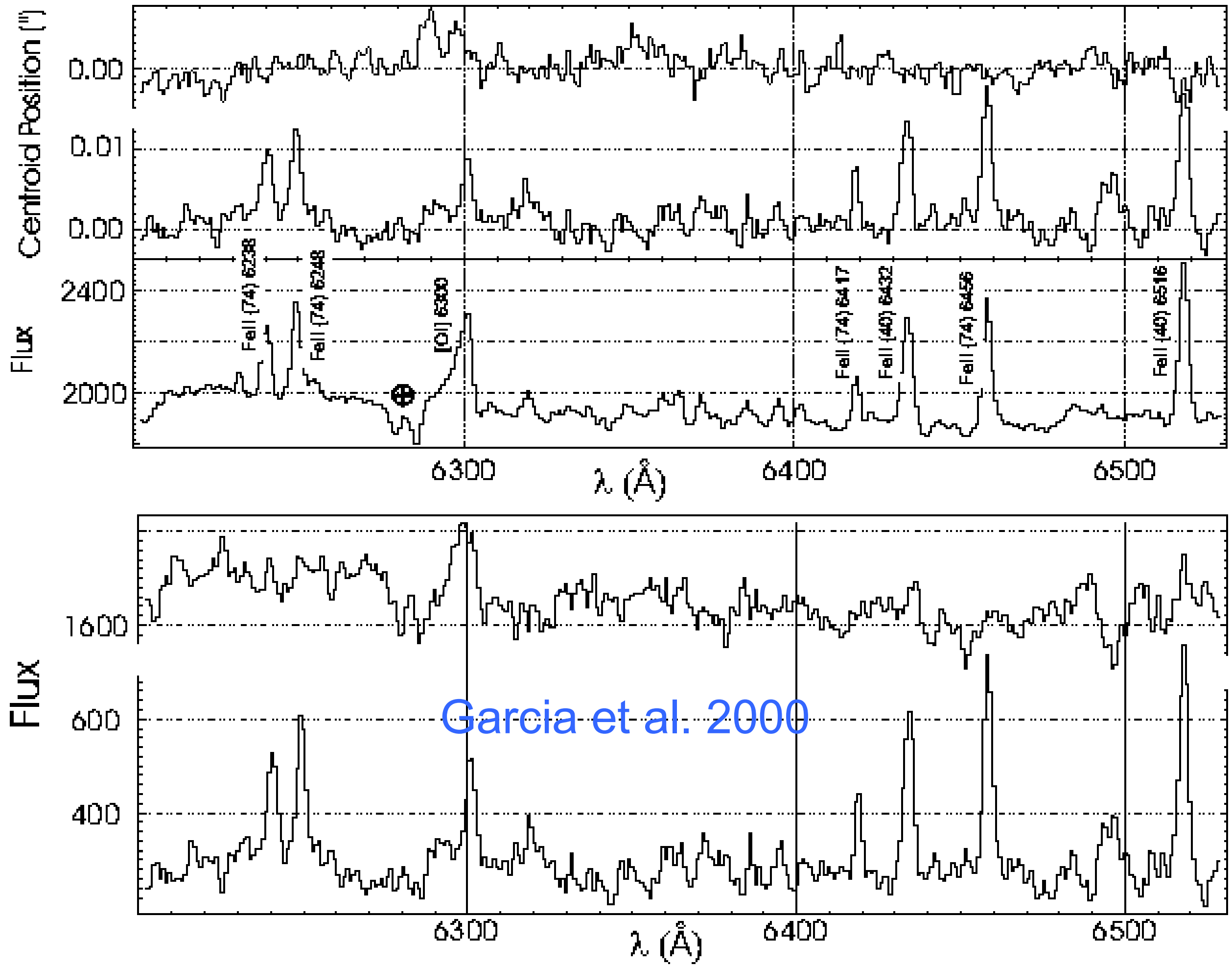
- SAURON vs OASIS



# Pushing the limits – 2
# Super resolution

- Follow the barycenter… *down to milliarcseconds*






$\perp$

$=$

**Total**

*Source 1*

*Source 2*

# Implications – I
# Need for a better characterisation

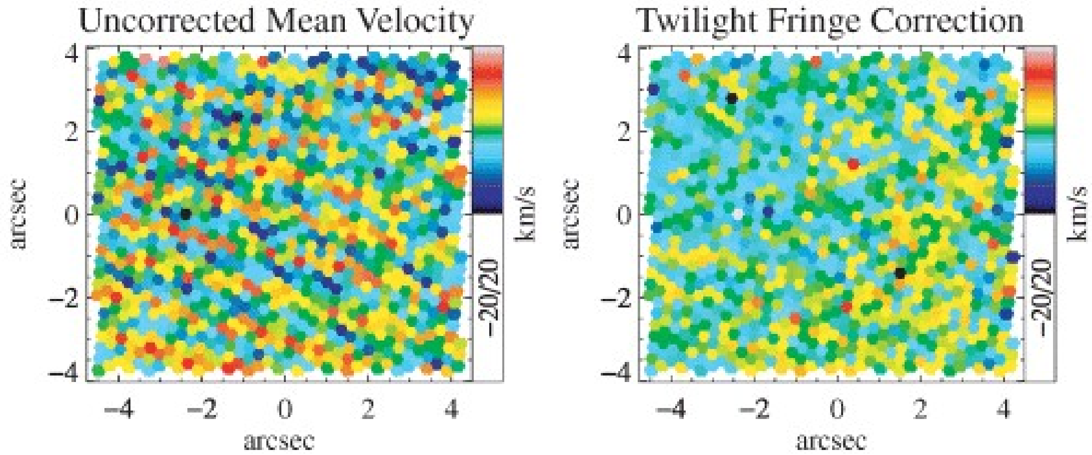
- A good, validated, *Calibration system*
- Stability of the instrument & telescope
- Taking into account, e.g. stray light

- Characterisation of the Detectors

- Why is all this needed ?

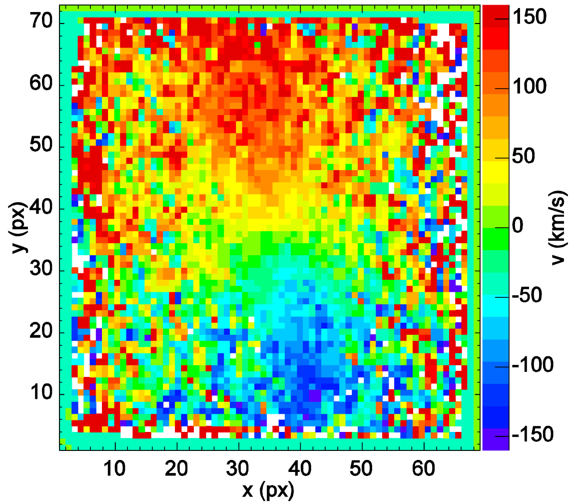
  - Illustration: zebras…

# Implications – I
# Better characterisation




OASIS

McDermid et al. 2006



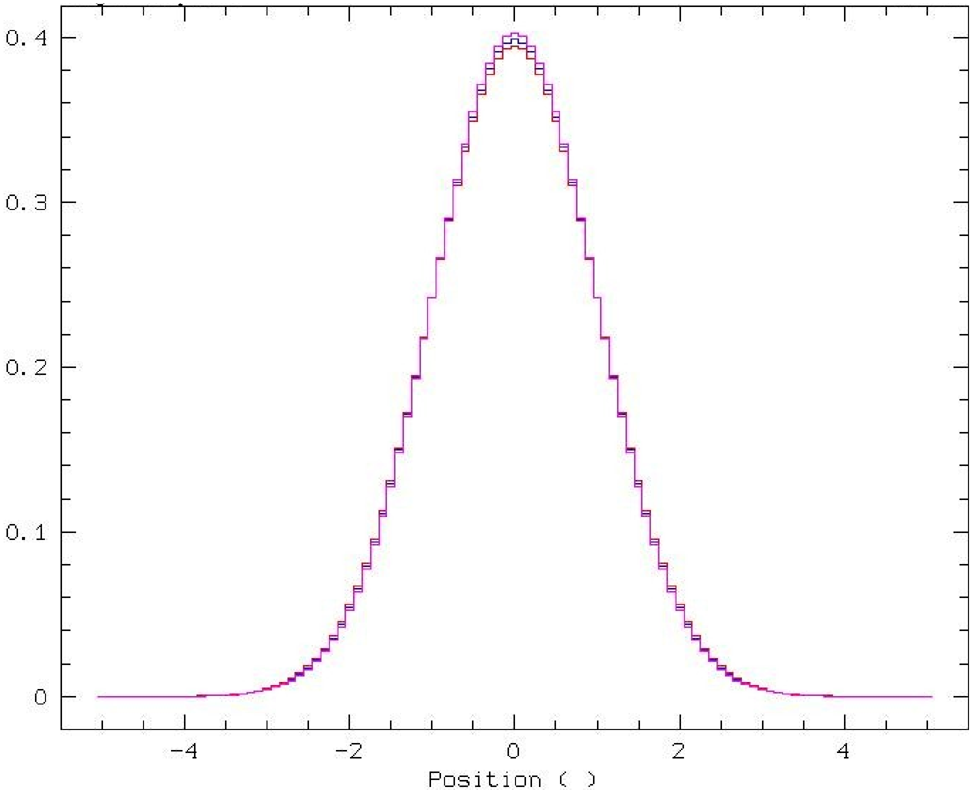

SINFONI data on NGC 4486a

Nowak et al., submitted

Fringing in VIMOS ➔ ***see poster 14 by Jullo***

# Implications – I
# Better characterisation

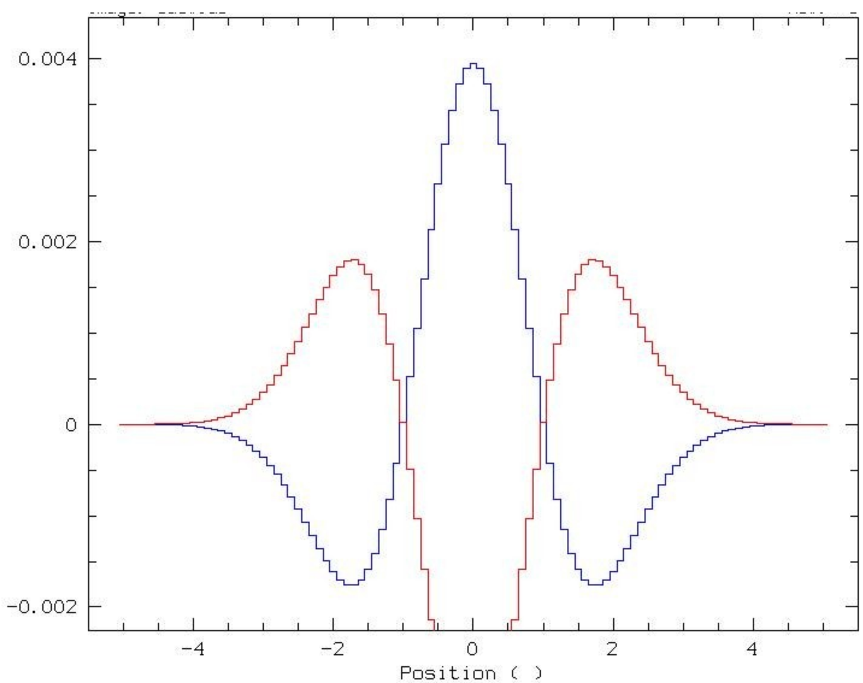
- Spectral (spatial) PSF **variations** over the field, with λ ?
  - ➔ ***See poster 18 on VIMOS by Kuntschner***
- Varying sampling
- Not perfect wavelength calibrations

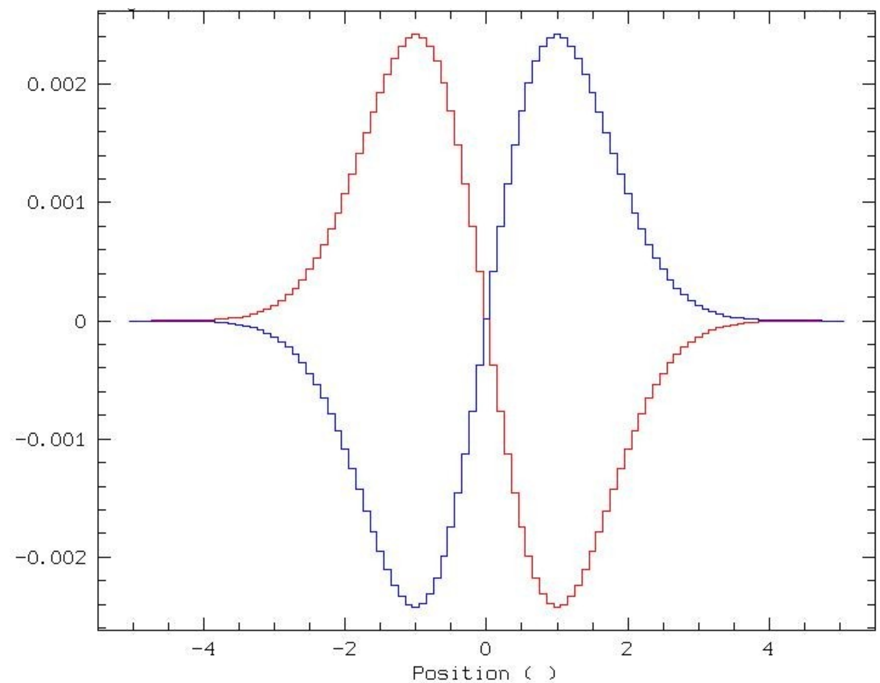



- Gaussian emission-line
  - Change the sigma by 1 %
  - Change the centroid by 1 % of the sigma
- The lines are barely distinguishable

# Implications – I
# Better characterisation

- Residuals ~ 0.5-1.0 % of the peak intensity

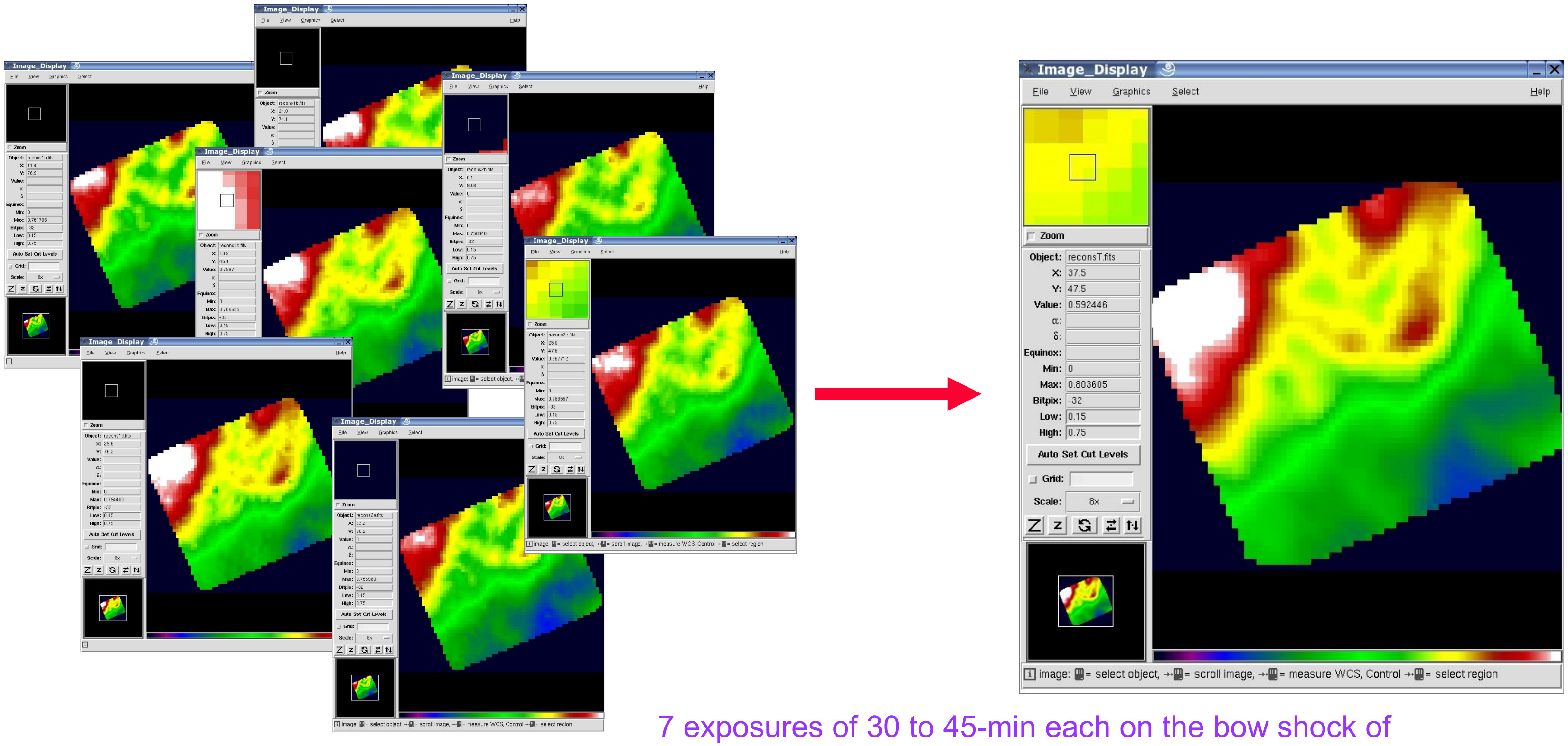



- *Major issue when the sky background ≥ object*
  - Deep exposures, near infrared…
  - ➔ ***See poster 24 by Modigliani (SINFONI)***

# Implications – II
# Need for new tools

- Mosaicing, Binning
- *Optimal* summation, normalisation, positioning
- Smoothing (spatially & spectrally)
- Deconvolution

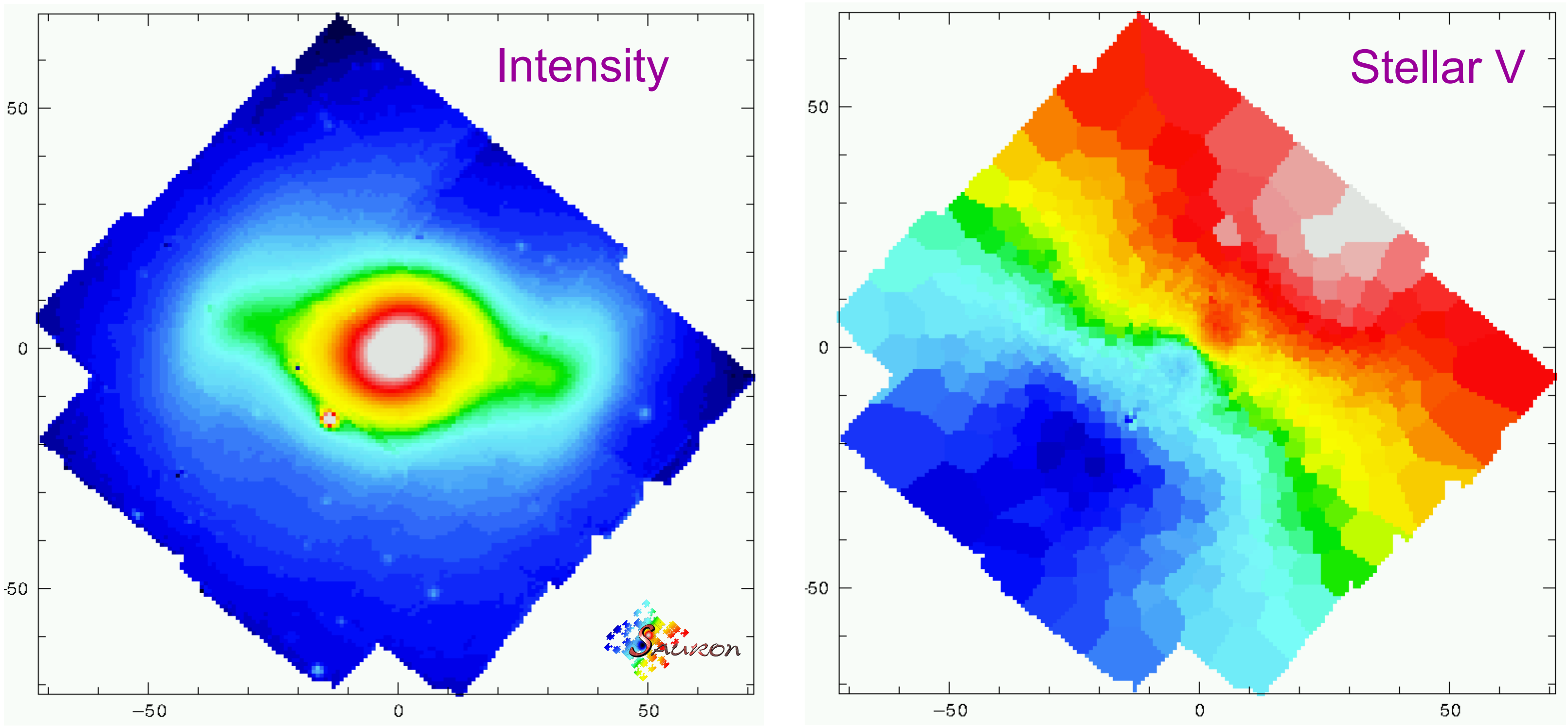


7 exposures of 30 to 45-min each on the bow shock of NGC 4258 (obtained with OASIS at CFHT). **P. Ferruit**

# Implications – II
# Need for new tools

- Mosaicing and binning with IFS !
  - **36 fields, more than 30 000 independent spectra**

    ***(and only 1/24 of MUSE data volume for 1 expo)***
  - ***Optimal summing, binning → requires noise propagation***




***Jourdeuil et al., in preparation; Binning scheme: Cappellari & Copin***

# Implications – II
# Need for new tools

- DRIZZLING:
  - Improving the sampling of poorly sampled images (HST era)
  - See e.g. ***Hook & Fruchter, 2000, ADASS #216*** and references therein
- A natural extension to 3D spectroscopy
  - Handling data cubes as stacks of monochromatic slices ?

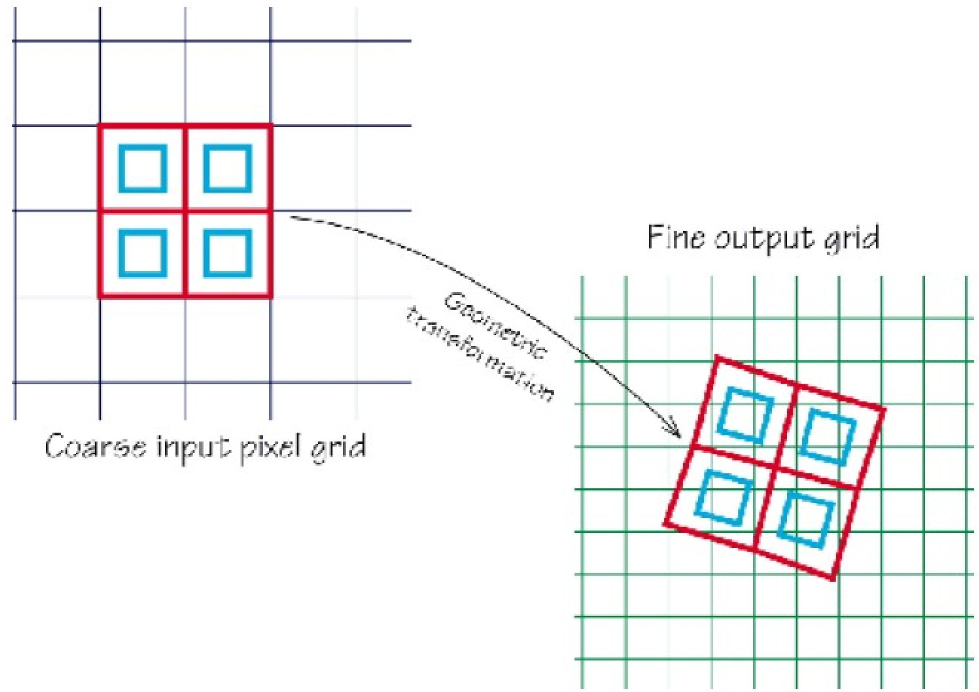
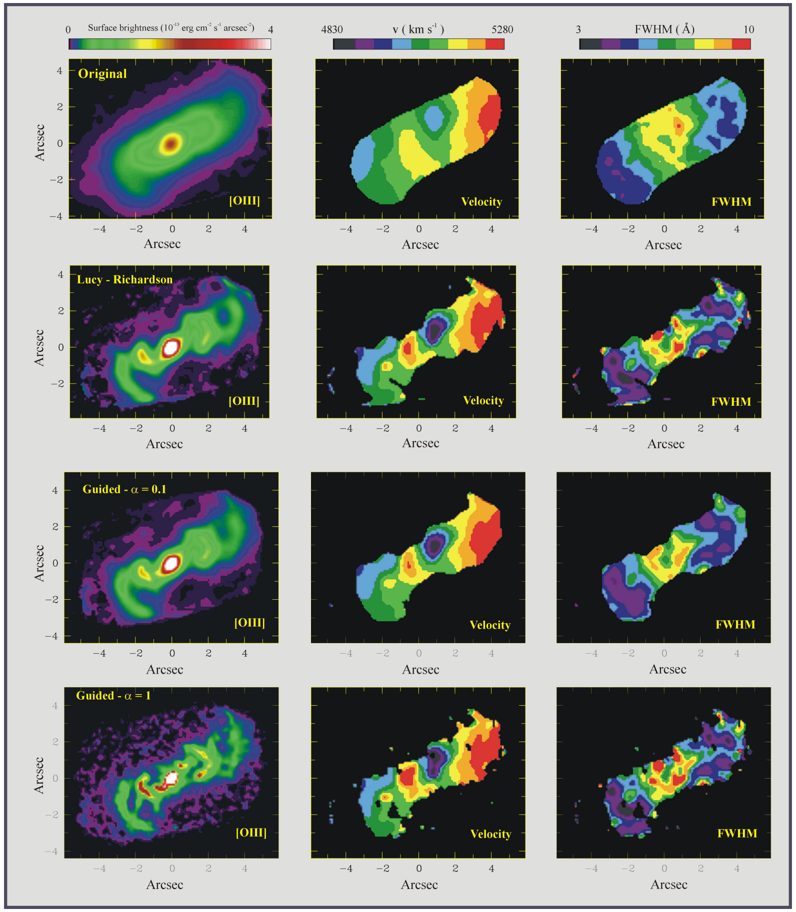



**Figure 2:** Illustration of how the drizzling method transforms an input pixel onto the selected output grid and showing the pixel shrinkage and general geometric distortion which can be included.

Additional corrections (distortion, atmospheric refraction) to be applied at the same time

# Implication – II
# Need for new tools




- Deconvolution:
  - Guided or not
  - To be adapted to 3D

# Implications – III
# Need for a good calibration plan…

- What is a science data product ?

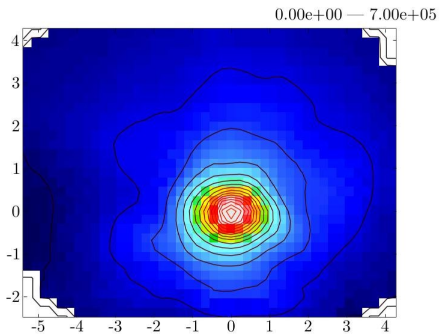
- Example:
  - FLAMES pipeline : amazingly good
    - But…

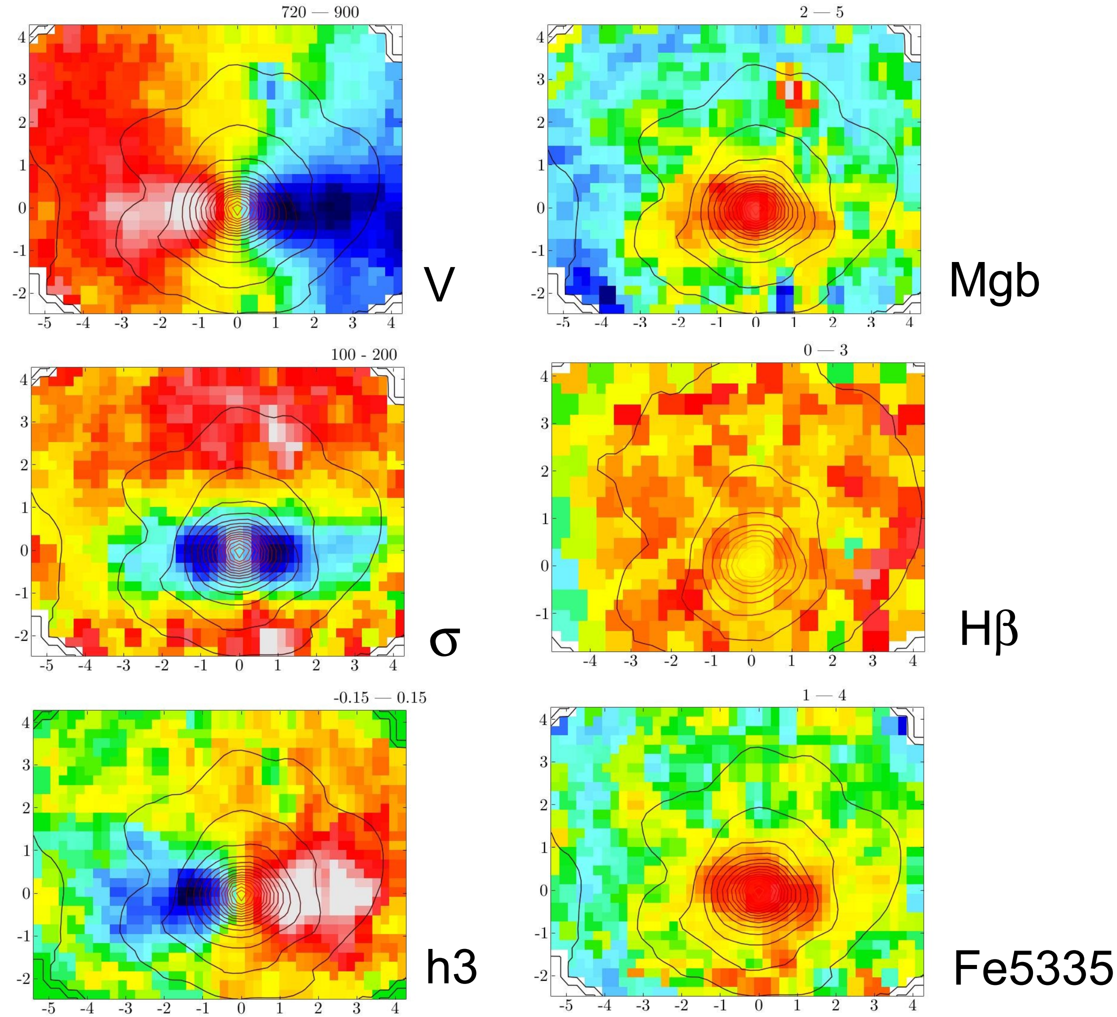
  - Where are the flux standards?

→ Archive ?
→ Which standard ? ***(spectral resolution, calibration!)***
→ UVES calibrated spectra ? (secondary…)

# Implications – III
# A good calibration plan

**FLAMES/ARGUS mode: 2 domains (Hβ, Mgb, Fe5270, Fe5335)**




**R=12000**

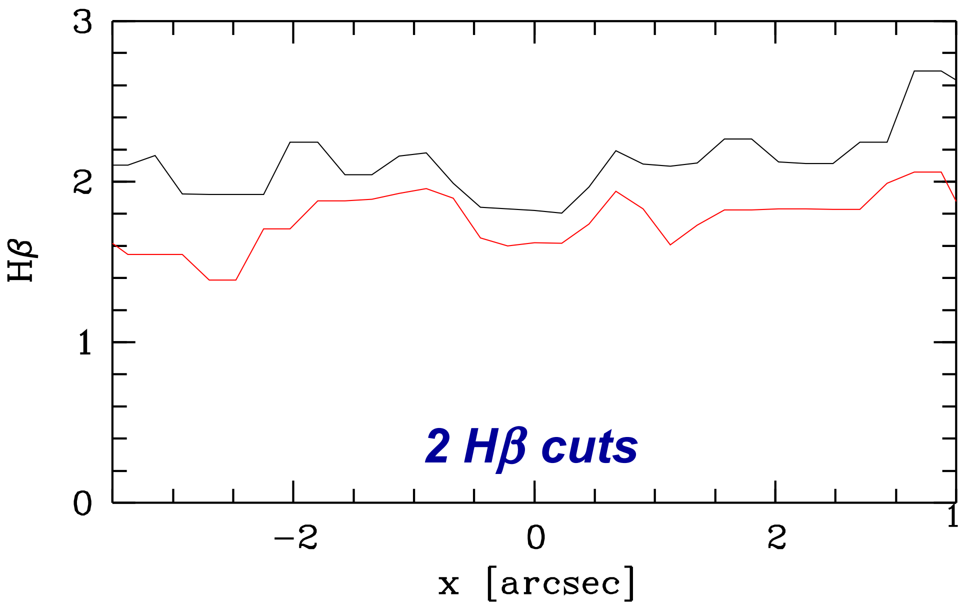
**➔ Stellar population study**

***& link with the dynamics***

*Emsellem, et al., in preparation*

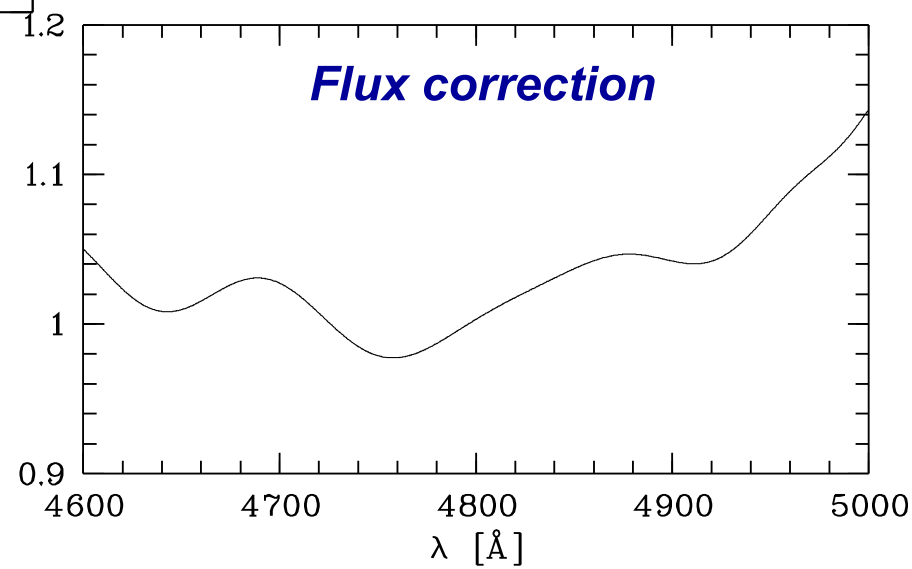
# Aging Stars

## FLAMES/VLT – ARGUS mode (L3)




*5-7 Gyrs ?*

*10-12 Gyrs?*




*Emsellem, et al., in preparation*

# Noise propagation and you...

- 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

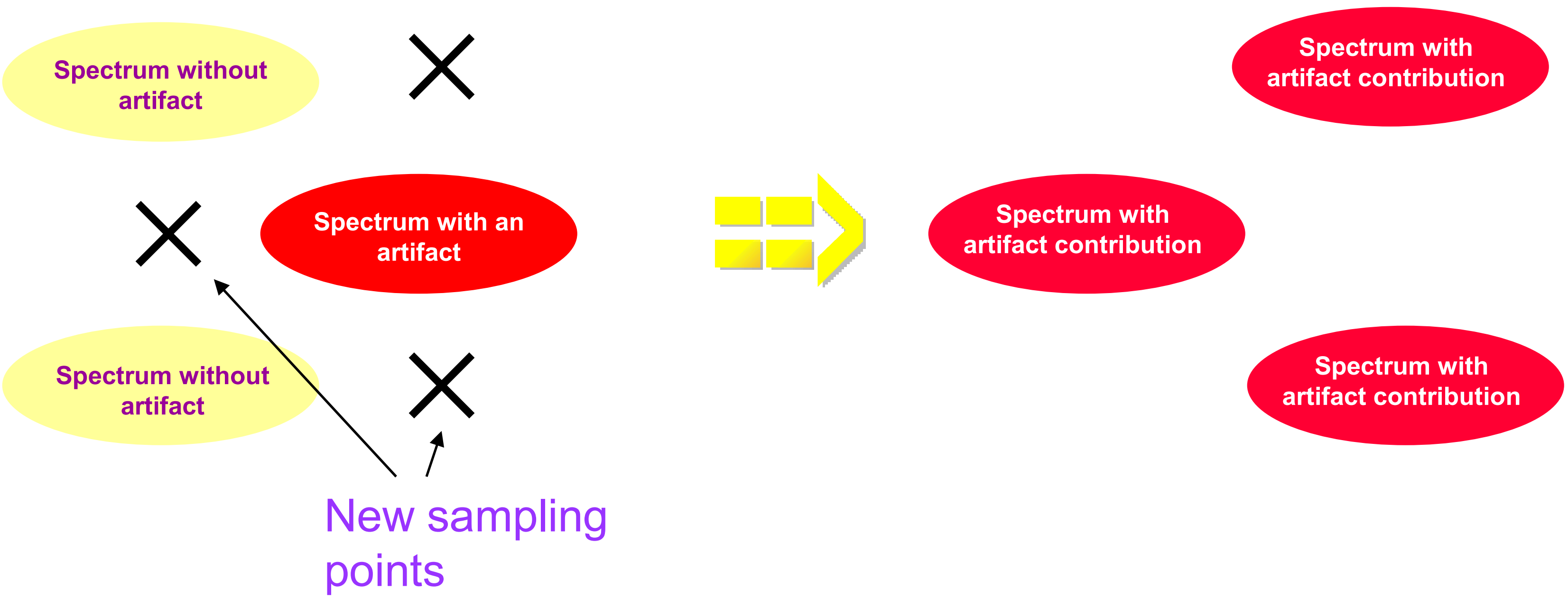
➔ *see poster 11 on X-shooter (and also poster 10 by Grado)*

The COBE data analysis = good example of how the noise and bias levels can tracked when conducting an analysis of a dataset

# The fear of 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?

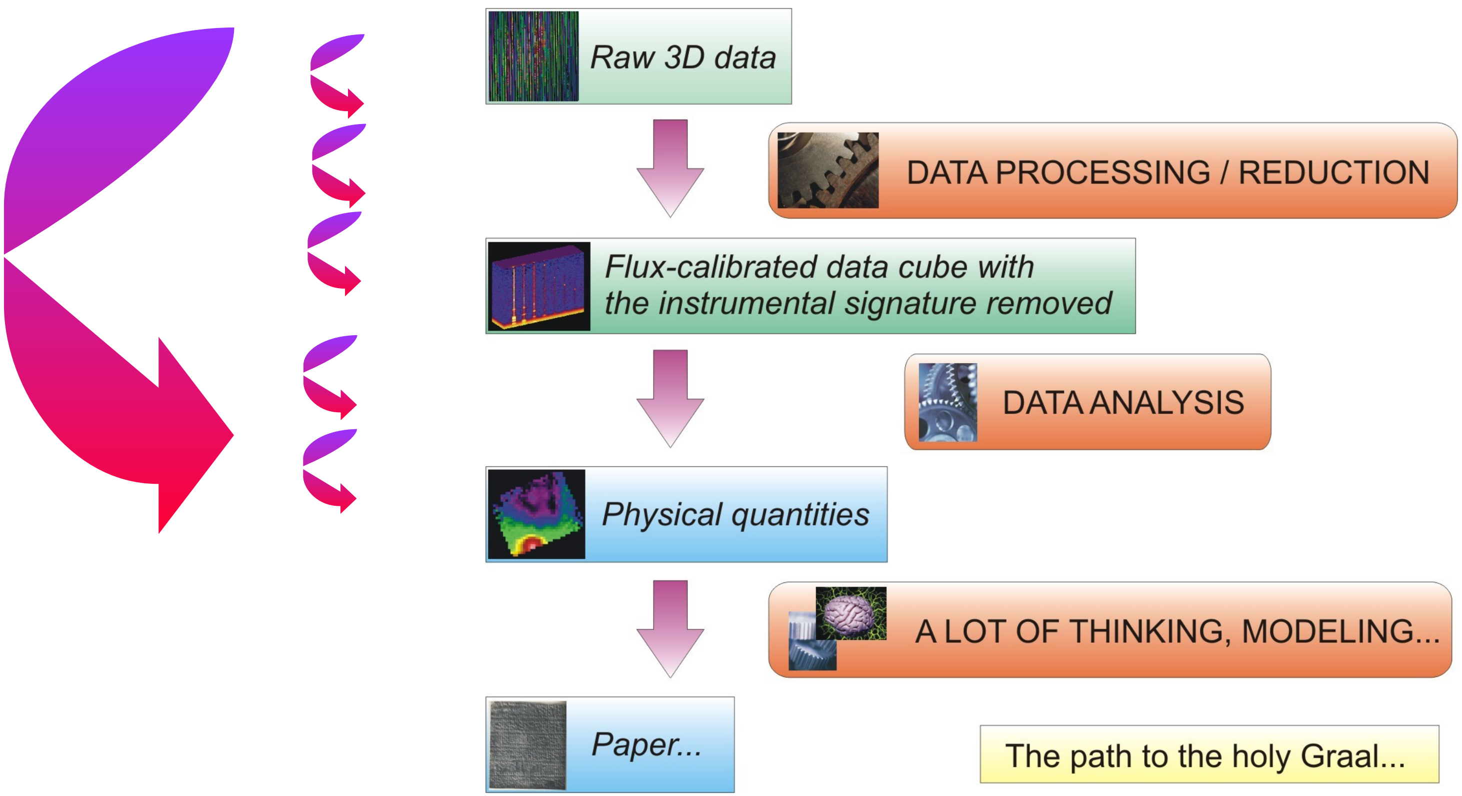
# Propagation of artefacts




- Artifact has been
  - spread
  - attenuated: less likely to be identified

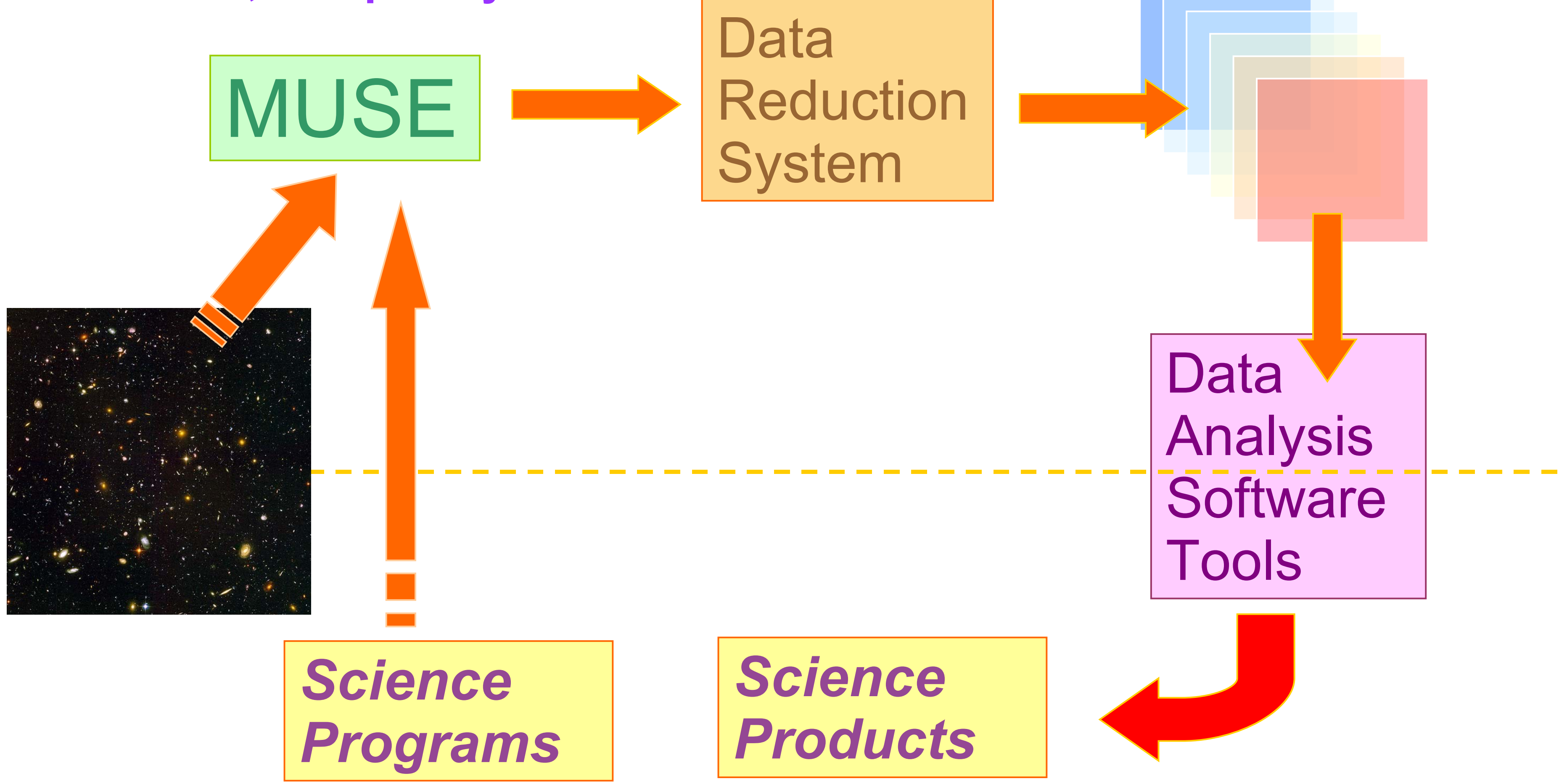
# The all-in one solution ?

- *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
  - ➔ real nightmare (and a 3D one!)
    - “less” true for densely-packed fiber systems and image slicers ?



# Data Analysis Software Tools for MUSE

- **Extract the best science products from MUSE cubes**
- **Volume, complexity…**



# Data analysis software tools for MUSE

DATA ANALYSIS TOOLS (non-exhaustive list !)

Sky subtraction tools

Image reconstruction tools

Deconvolution tools

Atmospheric refraction correction tools

Mosaicing tools

Visualisation tools

Crowded-field spectro-photometric tools

Model-fitting tools

Stellar-continuum fitting tools

Emission-line fitting tools

Data-mining tools

Generic image and spectrum analysis tools

Tools for data processing / reduction

Tools for data handling, preparation and visualisation

Tools to extract physical quantities from the data

# Conclusion

- Development of the (automated ?) tools to analyse the huge data sets of the next generation of instruments.
- Keep track of noise and systematic errors
  (tricky but good for scientific health).
- Characterisation of the instrument (+ reduction software)
- Adapted calibration plan + ***CALIBRATION PROPOSALS***
- Need for a good (parametric ?) model
- Most statements not specific to IFS

# Perspectives

- Software on *realistic* data: *Instrumental Numerical Model*
- Data Reduction Software + DAST

- Coordination!