Constraining the Fine-structure Constant at z ~ 2.5 using Emission Lines

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in collaboration with
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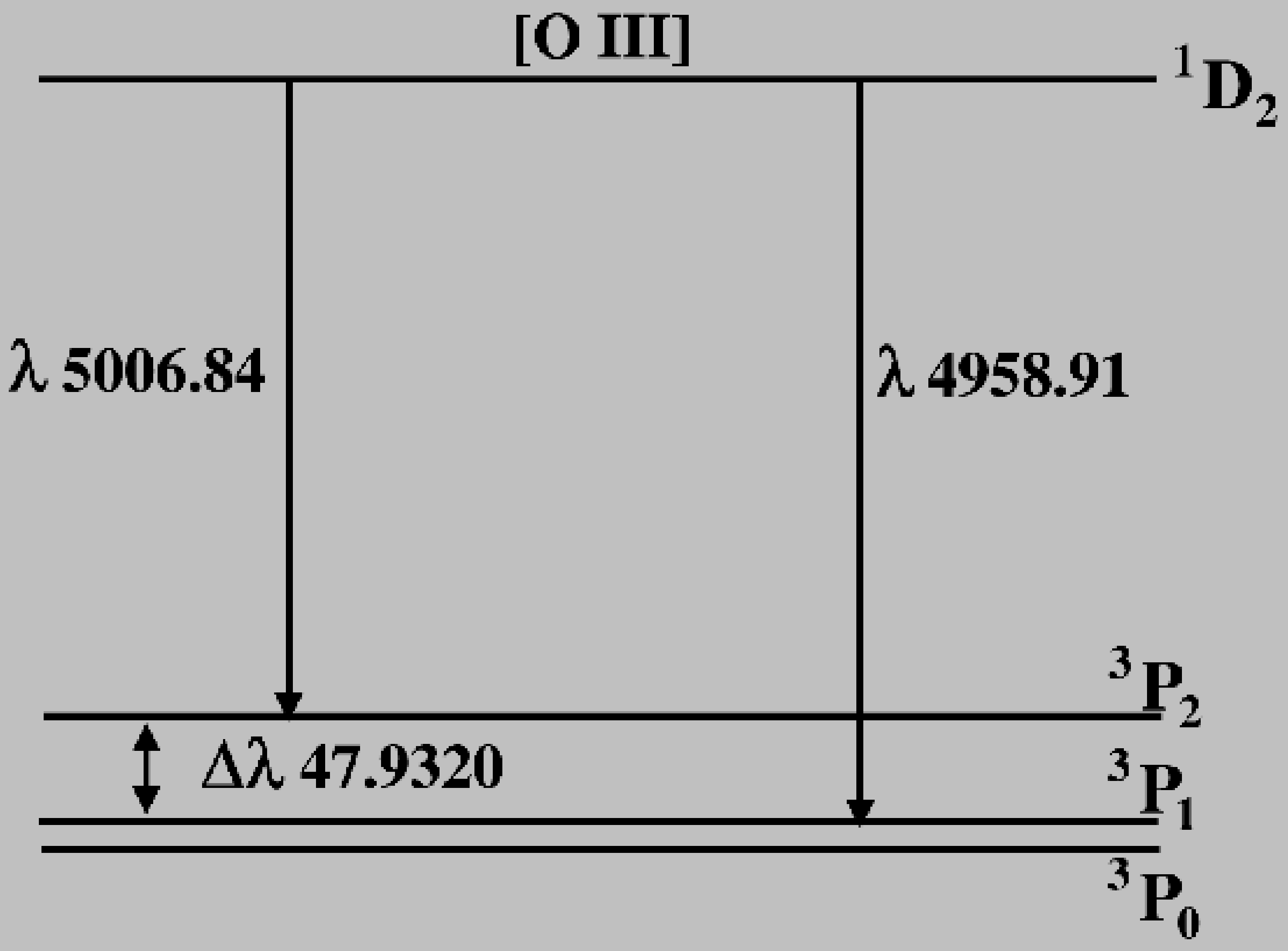
Outline

- Background (past research, physical foundation)
- Observational idea
- Data, reduction
- Results
- Biases and future possibilities

The method

Bahcall, Steinhardt & Schlegel (2004) revived an old method to constrain variation of the fine-structure constant using the wavelength separation of the [O III] lines at 495.9 and 500.7 nm

The [O III] transition



Bahcall et al (2004)

The method

Bahcall, Steinhardt & Schlegel (2004) revived an old method to constrain variation of the fine-structure constant using the wavelength separation of the [O III] lines at 495.9 and 500.7 nm

The wavelength separation is set by LS-coupling so depends on α^4.

This would require very good absolute wavelength calibration, but the wavelengths themselves depend on α^2 so

$$R = \frac{\Delta\lambda}{\lambda_1 + \lambda_2} = \frac{\nu_2 - \nu_1}{\nu_2 + \nu_1} \propto \alpha^2$$

A change in wavelength separation of 0.1Å gives $\Delta\alpha/\alpha_0 \sim 0.001$, 0.001Å gives $\Delta\alpha/\alpha_0 \sim 10^{-5}$

The advantages

- The [O III] originate from the same excited level
- The transitions are strongly forbidden => no optical depth effects
- Small separation => differential reddening is unimportant
- **Insensitive to multiple-components, variable excitation, variable isotopic mixtures**
- [O III] lines are very strong and can be observed with high S/N.

Moving on

The study by Bahcall et al (2004) was limited to $z<0.7$, but the most interesting region is $z\sim2$-3. Here the [O III] lines are in the near-IR

Downsides: Fainter because of the distance
Much more difficult because of bright sky and strong skylines.

Advantages: Quasars are intrinsically brighter at high redshift
Many skylines mean accurate wavelength calibration
Larger time-span improves constraints on time-evolution

The observational data

- 10 hours of VLT time in service mode (1 hr per target)
- 2 Radio galaxies, 4 QSOs with $1.981<z<3.126$
- 5 observations good for our purpose, 2 radio galaxies, 2 QSOs
- We use the ISAAC instrument to do near-IR spectroscopy. The resolution was the highest possible (R~10000). This gives about 1 Ångström per pixel (ideally we want to reach accuracies of 1/1000th of this.

Keeping track of uncertainties

Our (Monte-Carlo) method:

- Draw a random realization of each raw frame assuming Poissonian arrival statistics for photons
- Reduce the data for each such realization (301 in total for each object)
- The reduction is done with a special purpose pipeline
- Calculate all necessary quantities for each realization and use the variation between the realizations to construct a likelihood distribution for each quantity (we summarise using the 2.5, 50 and 97.5 percentiles)

Data reduction

Possibility of interpolation artefacts

- Cosmic ray removal
- Flat fielding and straigthening of images
- Individual frames must be matched
- Sky contribution must be subtracted
- Spectra must be extracted
- Wavelength calibration
- Position of [O III] lines must be measured and their separation constrained.

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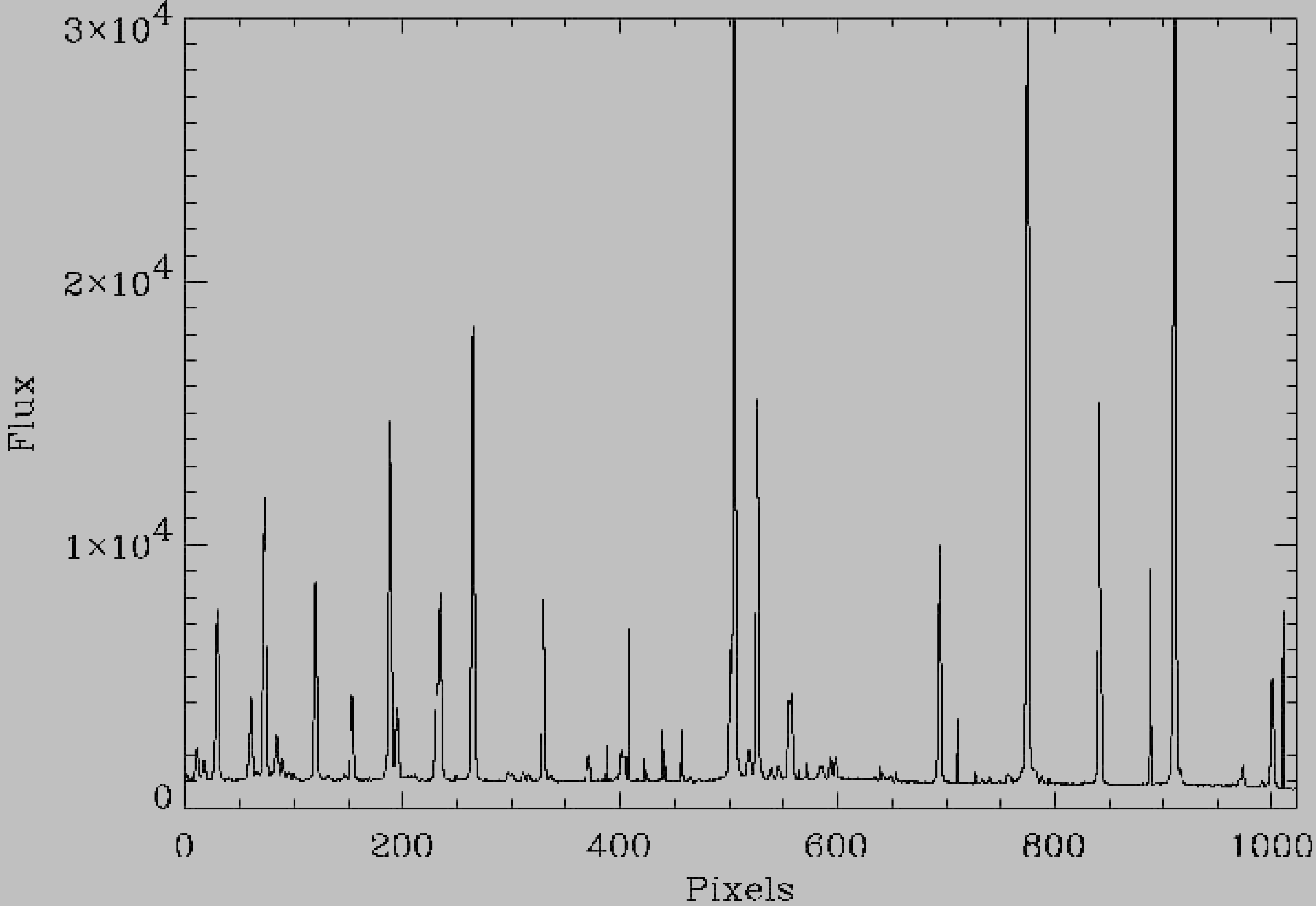
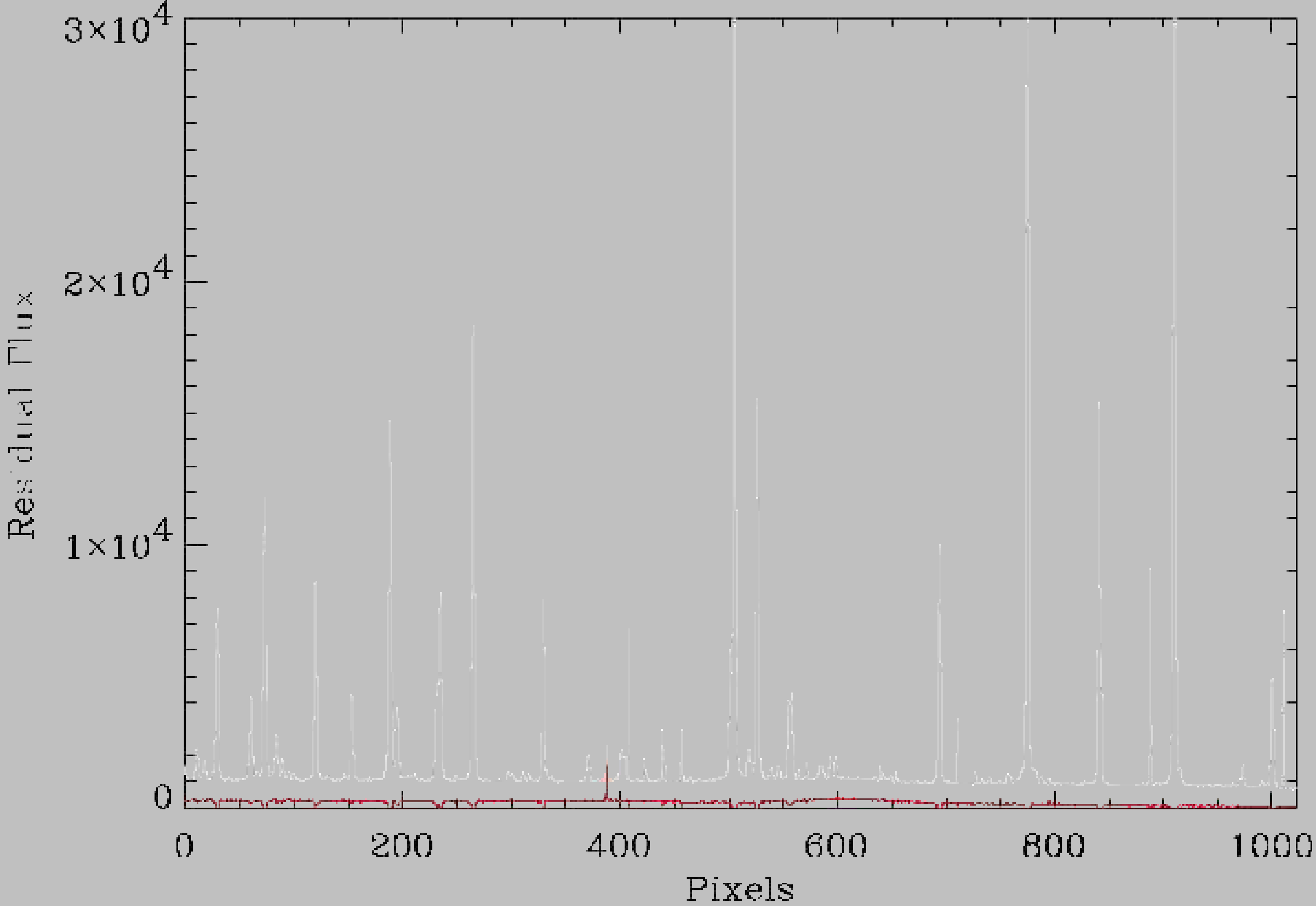
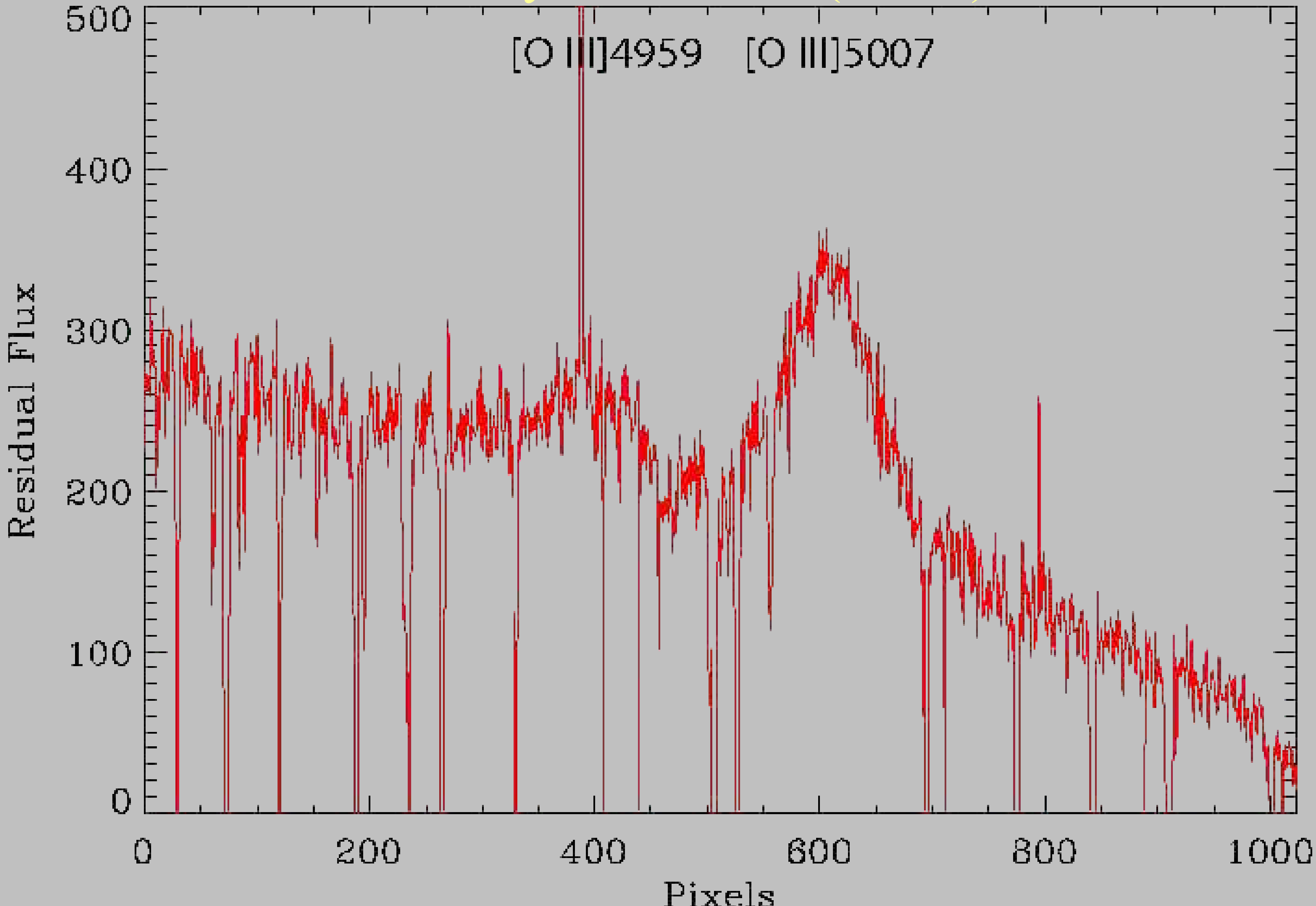
Raw spectrum



Sky subtracted



Sky subtracted (zoom)



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Wavelength calibration - OH lines

The OH lines result from roto-vibrational transitions in the OH radical occuring in a narrow layer in the atmosphere => similar physical origin.

The wavelengths of the lines are known from theoretical calculations (Rousselot et al 2000) calibrated by a furnace experiment (Abrams et al 1994)

The energy-levels have fine-structure because of Λ splitting (due to two possible directions of the electron angular momentum)

Typically 50-100 OH lines within the wavelength range of our spectra.

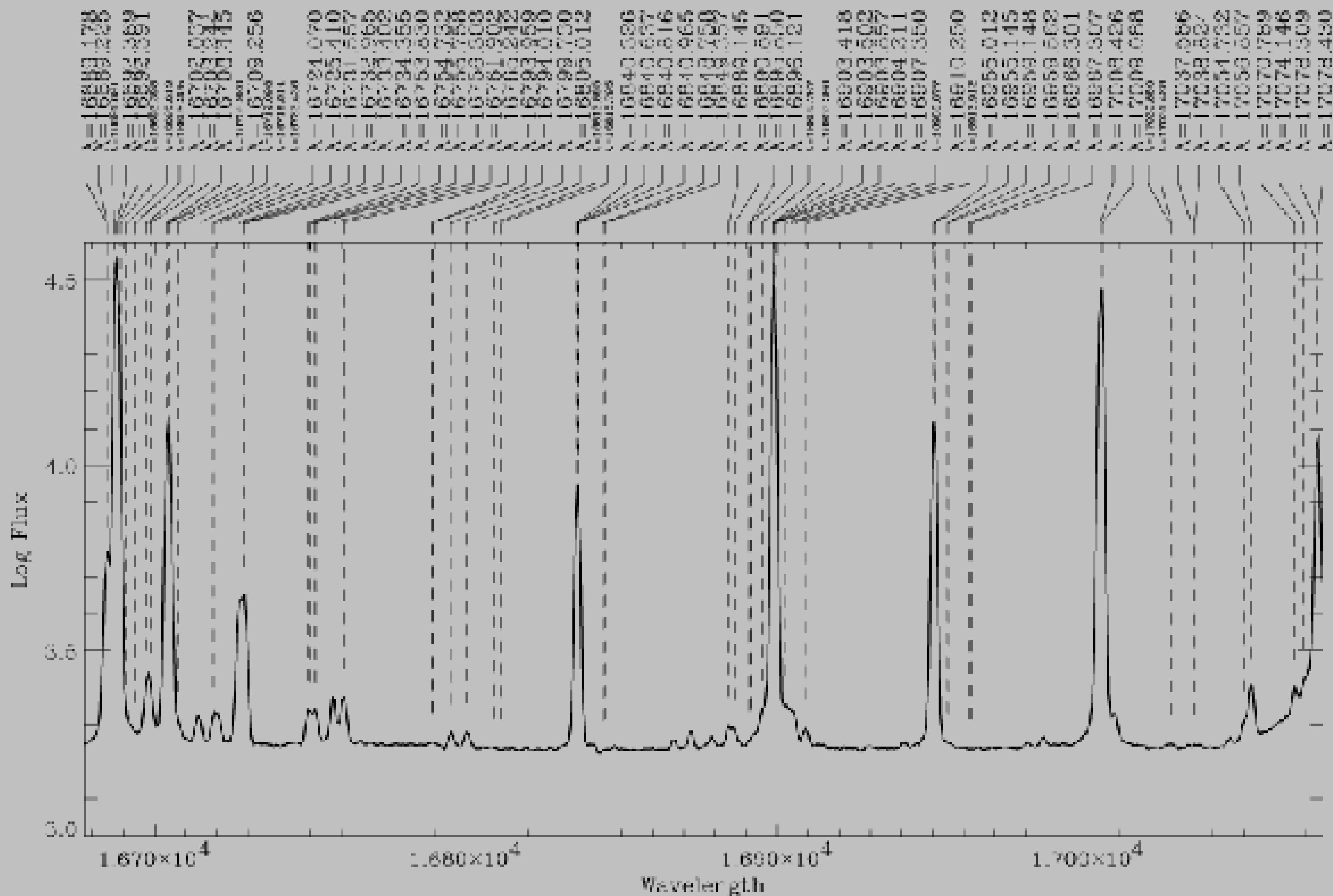
Our spectra do *not* resolve the OH lines fully

Steps in wavelength calibration

- Match observed sky-lines to theoretical library
- Tie all lines to have the same velocity width
- Tie all fine-structure transitions to have the same flux
- Constrain all lines to have the theoretically expected energy separation
- Find the optimal dispersion relation by comparing to the full sky spectrum (a third degree polynomial is sufficient)

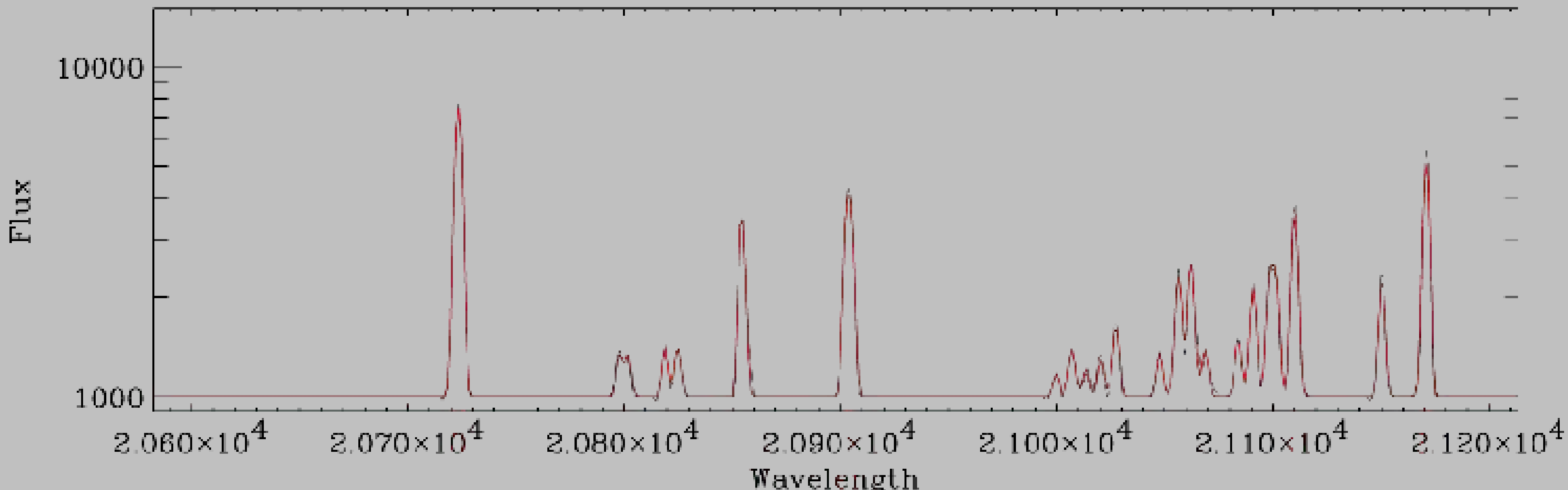
Steps in wavelength calibration

- Match observed sky-lines to theoretical library



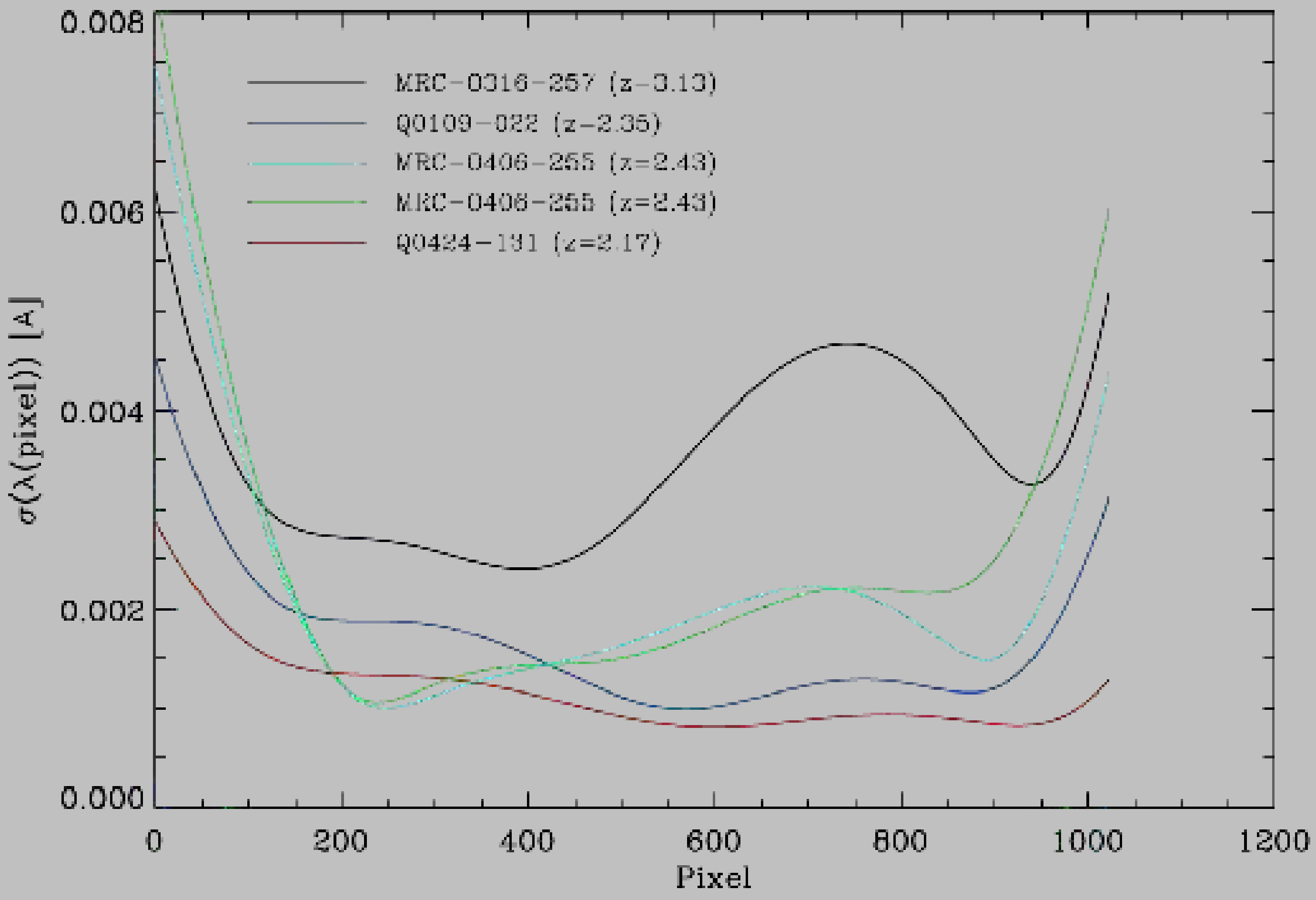
Steps in wavelength calibration

- Find the optimal dispersion relation by comparing to the full sky spectrum (a third degree polynomial is sufficient)



Generally very good fits when the doublet structure is taken into account

Wavelength accuracy



To assess the accuracy we use the Monte-Carlo realisations of the observations and compare the wavelength solutions.

Random errors ~0.004 Angstrom (10 times better than traditional techniques)

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Measuring the separation

Bahcall et al:

Shift and scale a B-spline representation of the QSO spectrum until the 4959 line matches the 5007 line.

Us:

- Shift and scale various smoothed representations of the QSO spectrum until the 4959 line matches the 5007 line.
- Fit the position of the 4959 and 5007 line cores separately

The strong sky-line residuals makes smoothing difficult, we have therefore tried B-splines, wavelets and a combination and take differences between these methods to be indicative of the systematic uncertainty.

Wavelet smoothing/filtering

We use the à trous wavelet transform. This takes a function f(k) and calculates a smoothed version at different scales c(j,k) from:

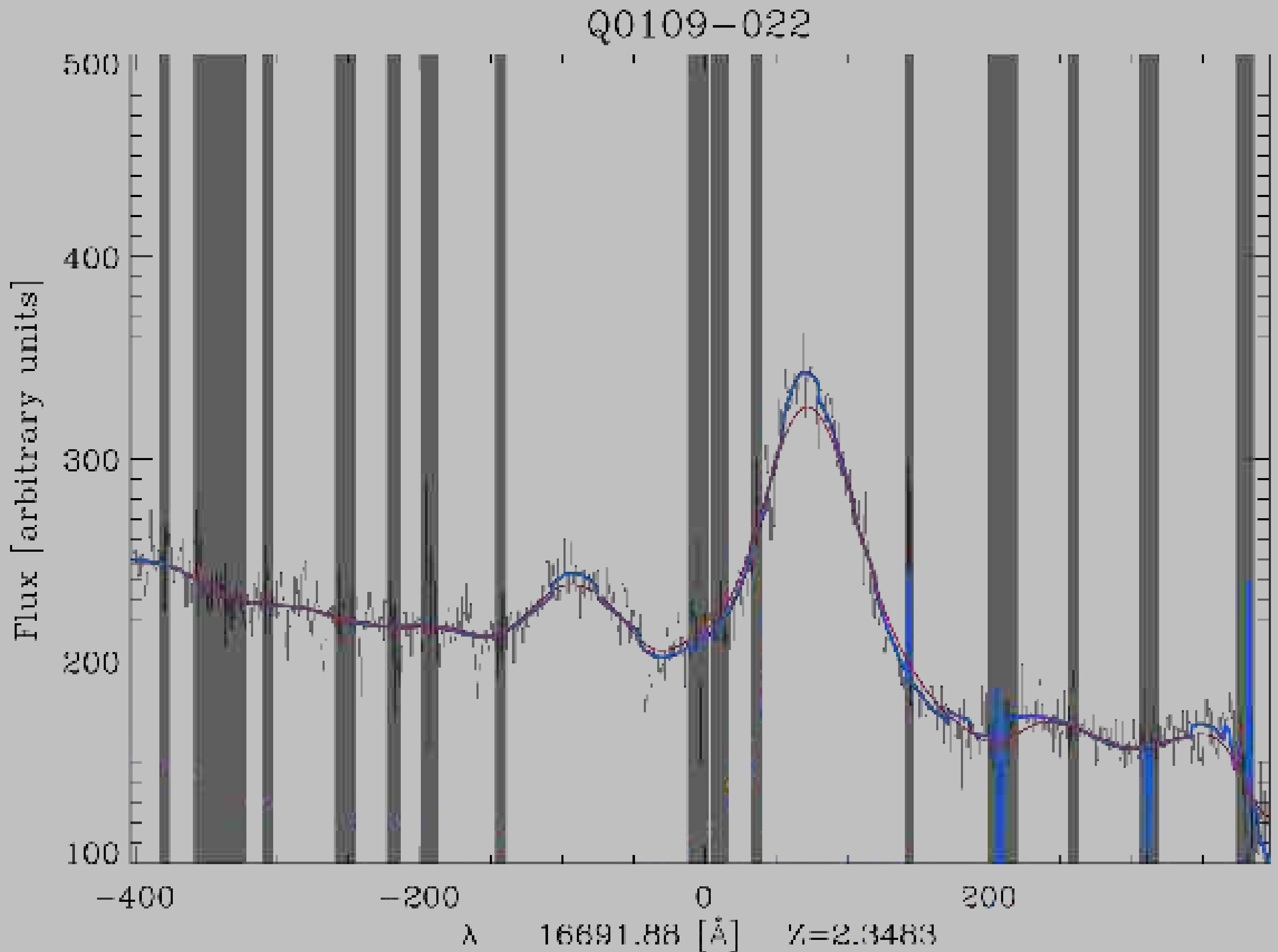
$$c(j+1,k)=\sum_l h(l)\,c\left(j,k+2^j l\right)$$

The wavelet coefficients, w(j, k) are the differences between consecutive filtering scales c(j, k)

We then use a noise model to estimate what wavelet coefficients contain signal and reconstruct the spectrum from these:

$$f_{rec}(k)=c(J,k)+\sum_l M(l,k)\,w(l,k)$$

Where c(J) is the smooth final spectrum and M(j, l), the multi-resolution support, is one for significant coeffients and zero otherwise



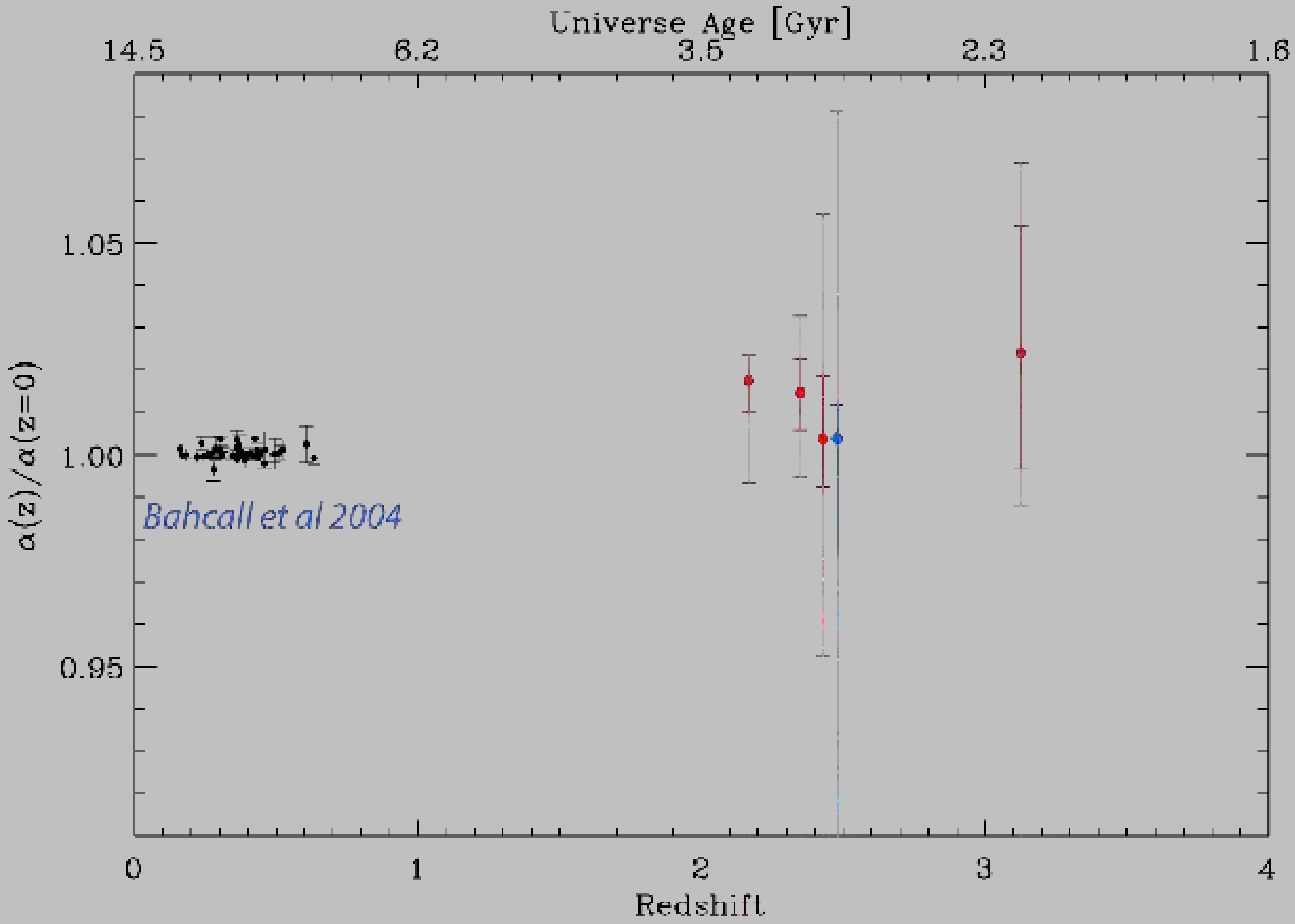
– Wavelet smoothed
– Wavelet filtered spectrum

Results

Name	Redshift	$\alpha(z)/\alpha(0)$
MRC-0316-257	3.1261	$1.0242^{-0.0276}_{+0.0297}$ (rand) $^{-0.0361}_{+0.0446}$ (sys)
Q0109+022	2.3482	$1.0146^{-0.0086}_{+0.0080}$ (rand) $^{-0.0200}_{+0.0183}$ (sys)
MRC-0406-255	2.4280	$1.0039^{-0.0118}_{+0.0146}$ (rand) $^{-0.0513}_{+0.0530}$ (sys)
MRC-0406-255	2.4282	$1.0039^{-0.0278}_{+0.0078}$ (rand) $^{-0.1181}_{+0.0773}$ (sys)
Q0424-131	2.1666	$1.0175^{-0.0074}_{+0.0054}$ (rand) $^{-0.0242}_{+0.0063}$ (sys)

All uncertainty estimates are 95% c.f (“2σ”)

The dependence on redshift



The time evolution of α

Following Bahcall et al we fit:

$$\alpha(t)^2 = \alpha_0^2 \left(1 + S\,H_0 t\right)$$

Ignoring systematic errors we get:

$$\frac{\alpha(t)^2}{\alpha_0^2} = 0.9984 \pm 0.0016 \qquad S = 0.0064 \pm 0.0058$$

Including systematic errors (assumed symmetric) we get:

$$\frac{\alpha(t)^2}{\alpha_0^2} = 0.9992 \pm 0.0016 \qquad S = 0.0032 \pm 0.0060$$

$$\frac{1}{\alpha}\frac{d\alpha}{dt} = (1.146 \pm 2.15) \times 10^{-13}\, yr^{-1}$$

All uncertainty estimates are 95% c.f (“2σ”)

What could go wrong?

Wavelength calibration:

- The OH line wavelengths could be systematically offset, unlikely, but conceivable.

Emission line measurements

- The [O III] lines could be affected by other emission (typically iron-lines)
- Hβ emission could affect the 4959 line (but not the peak position?)

More?

Summary/future

- We have constrained $\alpha(z)$ at $2<z<3$ using emission line measurements.
- The wavelength calibration achieved is the best ever for ISAAC data and is good enough to detect $\Delta\alpha \sim$ few x 10^{-5}
- The method suffers from fairly few systematic uncertainties in the physics and is therefore well suited for evolution studies
- Our results are consistent with zero change in α, but show consistently *high* values.
- To improve constraints dramatically we clearly need a larger sample => Concentrate on repeat observations of individual objects or large sample? High S/N and few objects or medium S/N and many objects?

Data reduction