Practical Spectro-Perfectionism in SDSS-III

Stephen Bailey *(LBNL), Adam Bolton (Utah), Joel Brownstein (Utah), Theodore Kisner (LBNL), Parul Pandey (Utah), David Schlegel (LBNL)*

As extragalactic spectroscopic surveys push to higher redshifts, the targeted objects are fainter and fainter, yet the night-sky foreground remains as bright as ever. This requires spectral extraction algorithms to push to new limits of signal-to-noise. The "spectro-perfectionism" algorithm of Bolton & Schlegel 2010 provides a framework to achieve Poisson-limited sky subtraction through the forward modeling of photons onto the spectrograph CCDs using a two dimensional point spread function (2D PSF). This method produces uncorrelated errors in the extracted spectra while fully preserving the input spectrum likelihood function given the raw CCD pixel data. A brute-force implementation of this algorithm would be computationally prohibitive. We present a practical implementation of this algorithm for the Baryon Oscillation Spectroscopic Survey (BOSS) of the Sloan Digital Sky Survey III (SDSS-III). This implementation handles the full complexity of real data while being computationally tractable on current-generation hardware. The gains from this implementation will increase the science reach of BOSS and will be critical for future redshift surveys such as the proposed BigBOSS project.

Motivation

BOSS: Sky subtraction and error accuracy are limiting factors

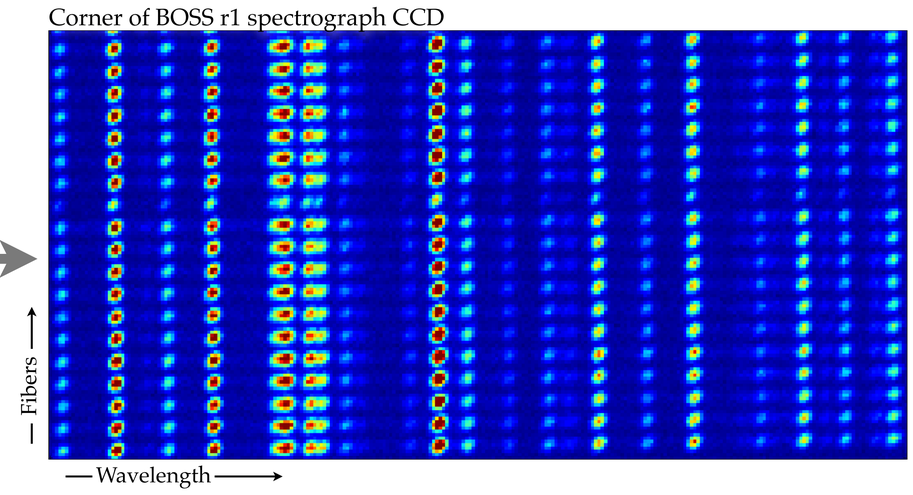
BigBOSS: Emission line galaxies (ELGs) barely visible amidst sky emission

1. Bright sky + faint sources + imperfect PSFs = need best possible spectral extraction
2. Mathematically correct extraction and error propagation:
   If PSF(x,y) ≠ P(x) Q(y) then "optimal extraction" isn't optimal
3. Spectral extraction as lossless data compression:

$$\sum_{\text{pix } i} \left[\frac{(\text{data}_i - \text{model}_i)}{\sigma_i}\right]^2 \quad \text{vs} \quad \sum_{\lambda} \left[\frac{(\text{flux}_\lambda - \text{model}_\lambda)}{\sigma_\lambda}\right]^2$$

Near the corners of the BOSS spectrograph CCDs, the PSF degrades

Corner of BOSS r1 spectrograph CCD



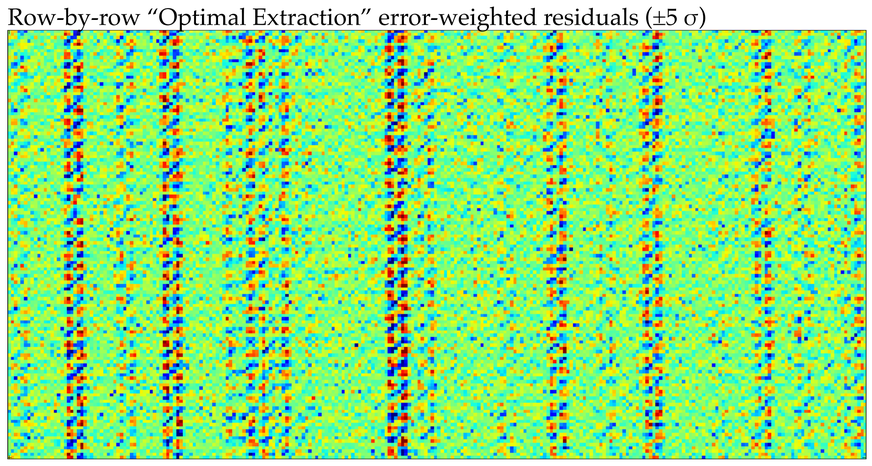
"Optimal extraction" is no longer mathematically optimal if

PSF(x,y) ≠ P(x) Q(y)

Results have big extraction residuals and lower classification/z efficiency

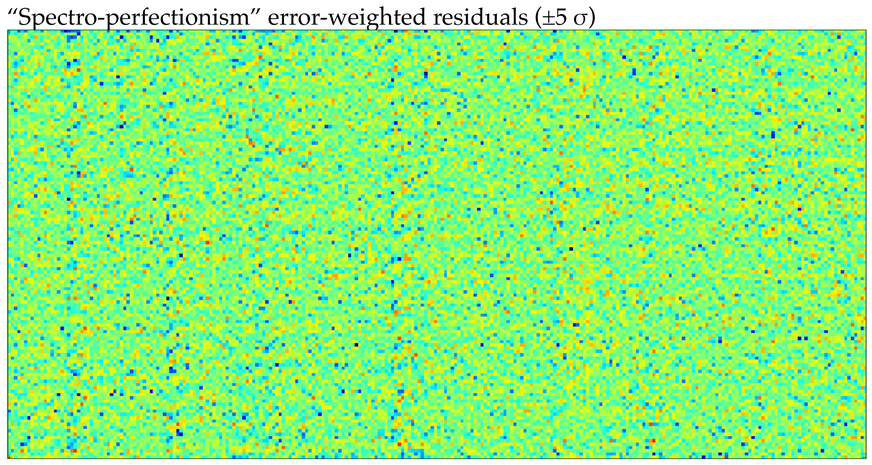
We need a better algorithm to extract faint sources

Row-by-row "Optimal Extraction" error-weighted residuals (±5 σ)



Modeling the 2D PSF produces much better residuals

"Spectro-perfectionism" error-weighted residuals (±5 σ)

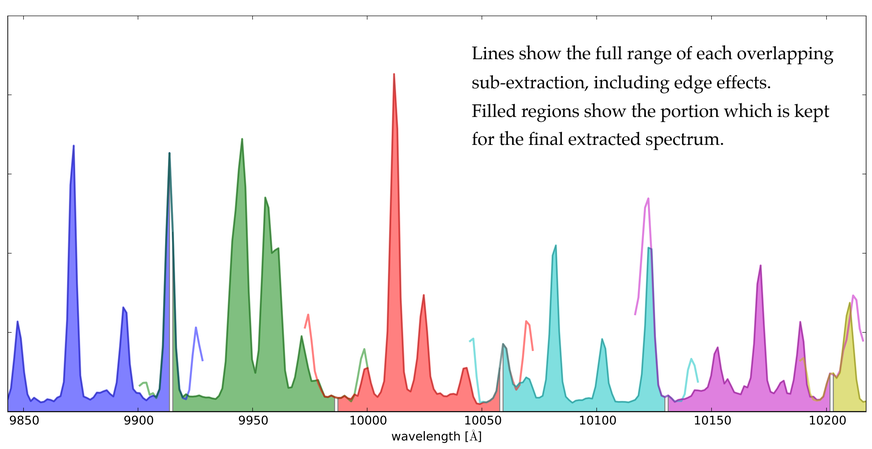


The main problem:

this is computationally expensive

Dividing the problem into multiple overlapping subregions makes it computationally tractable:

- 1 hour/CCD frame on 8-core Xeon
- python prototype implementation
- feasible to implement for BOSS, BigBOSS



The Challenge

"Spectro-perfectionism" of Bolton & Schlegel 2010 solves the math, but the naive implementation is computationally prohibitive due to very large matrix inversions.

We need a practical implementation that works on real-world data.

Spectro-perfectionism is the baseline algorithm for BigBOSS extractions; implementing it on BOSS data will improve BOSS science and provide a real-world test case.

Math

Spectrum f projected onto pixels p with matrix $\mathbf{A}$ plus noise:

$$\vec{p} = \mathbf{A}\vec{f} + \epsilon$$

Extract spectrum f and covariance $\mathbf{C}$ using weights $\mathbf{N}^{-1}$:

$$\vec{f} = (\mathbf{A}^{\mathrm{T}}\mathbf{N}^{-1}\mathbf{A})^{-1}\mathbf{A}^{\mathrm{T}}\mathbf{N}^{-1}\vec{p}$$

$$\mathbf{C} = (\mathbf{A}^{\mathrm{T}}\mathbf{N}^{-1}\mathbf{A})^{-1} \longleftarrow \text{(2M x 2M) matrix inversion}$$

Diagonalize covariance matrix:

$$\tilde{\mathbf{C}} = \mathbf{R}\mathbf{C}\mathbf{R}^{\mathrm{T}}$$

Extracted spectrum with diagonal covariance:

$$\tilde{f} = \mathbf{R}\vec{f}$$

$\mathbf{R}$ is the "resolution matrix" used to project model spectrum m into the extraction basis with diagonal errors. Pixel- and spectral- χ^2 are now equivalent:

$$\chi^2_{\text{pix}} = (\mathbf{A}\vec{m} - \vec{p})^{\mathrm{T}}\mathbf{N}^{-1}(\mathbf{A}\vec{m} - \vec{p})$$

$$\chi^2_{\text{spec}} = (\mathbf{R}\vec{m} - \tilde{f})^{\mathrm{T}}\tilde{\mathbf{C}}^{-1}(\mathbf{R}\vec{m} - \tilde{f})$$

Implementation

Divide & conquer – many little matrix inversions instead of one big one:

1. Bundles of 20 fibers separated by gaps on the CCD:
   a. Decouple groups of spectra into separate uncorrelated extractions
   b. Use gaps to model scattered light not described by PSF
2. Extract overlapping subsets in λ; reassemble after discarding edge effects

Prototype algorithm implemented in python using scipy sparse arrays. Computationally tractable on current hardware:

- 1 hour per CCD frame on 8-core Xeon
- BOSS: 4 frames/exposure; BigBOSS: 30 frames/exposure

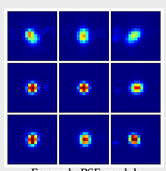
Ongoing Work:

Optimal sky subtraction, classification, and redshift fitting; pipeline glue, scaling performance, BOSS and BigBOSS simulations.

2D PSF Models

We measure the 2D PSF vs. (x,y) on the CCD using arc lamp exposures with isolated narrow emission lines. The PSF is modeled with either:

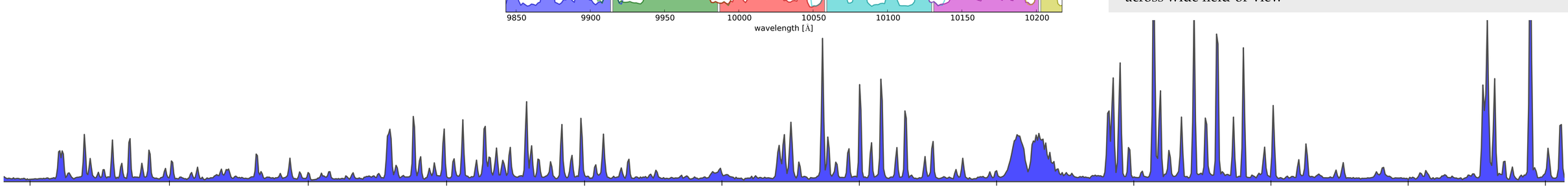
1. Gauss-Hermite polynomials — coefficients smoothly vary vs. (x,y)
2. Pixellated PSF — Taylor expand PSF images in (x,y):
   $\text{PSF}(x,y) = I_0 + xI_x + yI_y + xyI_{xy} + \ldots$



Example PSF models

Additional Benefits

1. Extract on any λ grid with diagonal errors: not tied to CCD pixel grid
2. Individual exposures extracted on same grid can be co-added without resampling and without introducing off-diagonal covariance
3. Sky model: separate instrumental variations from true sky variations across wide field-of-view



Contact: StephenBailey@lbl.gov

References: *Optimal Extraction*: Horne 1986, PASP 98, 609; *Spectro-Perfectionism*: Bolton & Schlegel 2010, PASP 122, 248; Bolton *et al.* 2011, arXiv 1111.6525