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Spectro-perfectionism for hi-fi spectroscopy

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Why?

We want to achieve full **spectral fidelity**, i.e. to reconstruct the original spectral information by removing the instrumental signature. This is relevant to all science cases requires high accuracy/precision/stability, such as the measurement of the variability of fundamental constants, the measurement of the redshift drift of distant sources, and the assessment of primordial nucleosynthesis from Deuterium abundance measurements. **While instrumentation and calibration have undergone a major overhaul in the last 20 years, data treatment is lagging behind.** The reason is that data reduction is still mostly based on reverse modeling: given the detector output, the input spectrum is recovered by tracing the signal along the echelle orders and integrating it along the transverse direction with an appropriate weighting ("optimal extraction", Horne 1986). While fast and robust, this method is generally wrong, as it assumes that the instrument point-spread function (PSF) is separable along the CCD axes.

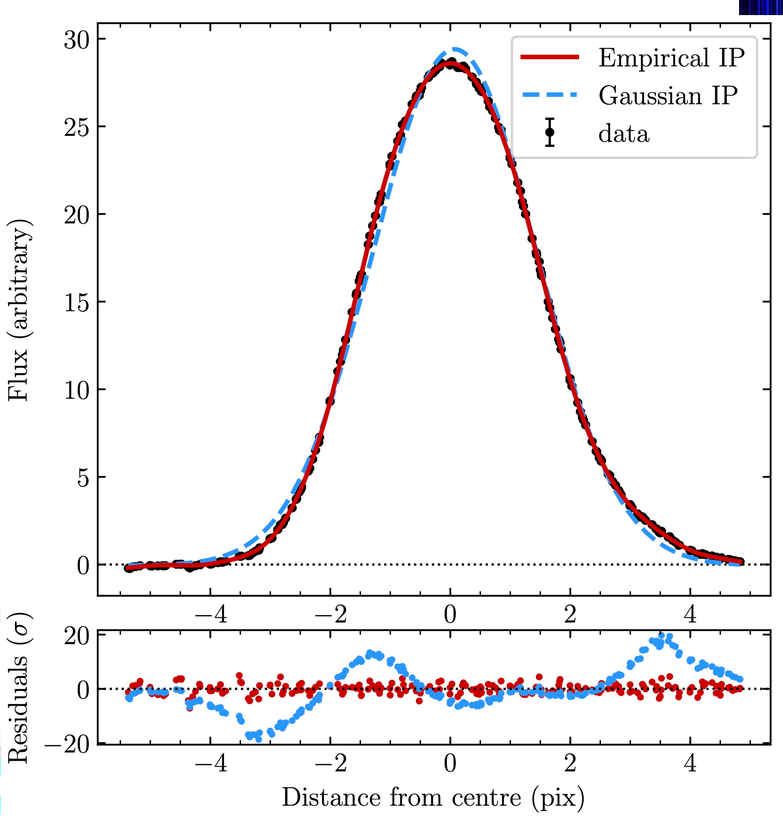
What?

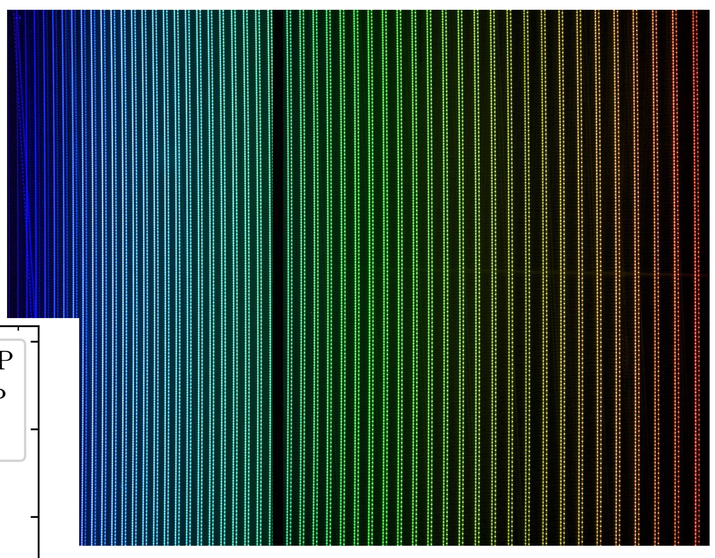
The correct approach to spectral extraction (**spectro-perfectionism**; Bolton & Schlegel 2010) is based on forward modelling: given the instrument characteristics, the detector output is interpreted as the result of a linear transformation of the input spectrum, which can be recovered by inverting the transformation itself. In vector terms: $\mathbf{p} = \mathbf{A}\,\mathbf{m} + \mathbf{n}$, where $\mathbf{m}$ is the input spectrum, $\mathbf{p}$ is the vector of pixel counts, $\mathbf{n}$ the error, and $\mathbf{A}$ the calibration matrix, encapsulating all instrumental effects. Data reduction is therefore represented as a two-step procedure: (1) the evaluation of $\mathbf{A}$; (2) the extraction of the spectrum as $\mathbf{f} = \mathbf{R}\,\mathbf{m} = \mathbf{R}\,(\mathbf{A}^T\mathbf{N}^{-1}\mathbf{A})^{-1}(\mathbf{A}^T\mathbf{N}^{-1})\,\mathbf{p}$, where $(\mathbf{A}^T\mathbf{N}^{-1}\mathbf{A})^{-1}$ is the pixel covariance matrix and $\mathbf{R}$ a resolution matrix that can be modelled from a diagonalisation of $\mathbf{A}$. **Despite its computational cost, spectro-perfectionism has been successfully applied to DESI** (Guy et al. 2023). We are now applying it **for the first time to a high-resolution super-stable spectrograph, namely HARPS@3.6m**.

How?

We are developing **HARPERFECT**, a Python library to extract HARPS spectra using the spectro-perfectionist approach. HARPERFECT uses the HARPS Laser Frequency Comb (LFC) to accurately model the instrument Instrument Profile (IP) and compute the calibration matrix **A**.

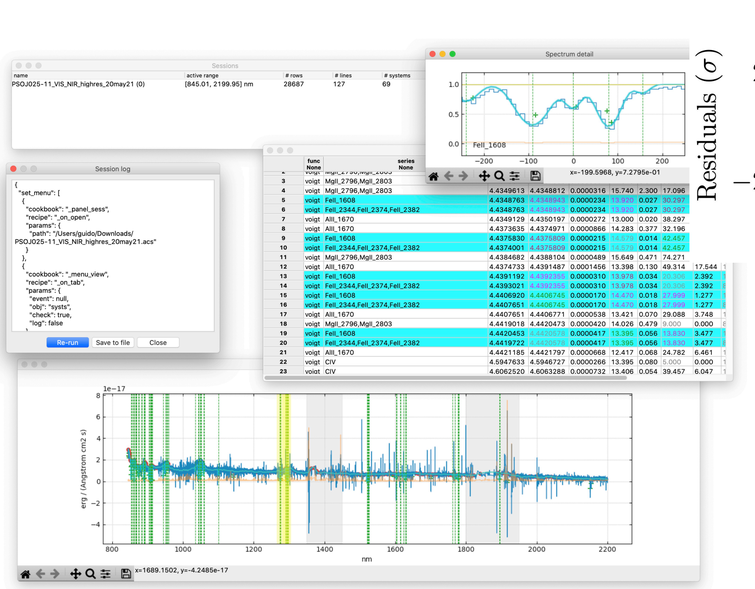
We already constructed a 1-d model of the HARPS IP using Gaussian Process regression (Milaković & Jethwa 2024). We are now implementing a **Convolutional Neural Network** to identify the relevant features that characterize the IP in 2 dimensions. The performance of IP deconvolution will be tested on simulated data and archival test data, under different CPU and GPU architectures. Lastly, HARPERFECT will be interfaced with the ESO HARPS pipeline and the Astrocook spectral analysis package.





⬆ ESPRESSO LFC, serving as an example of the data that will be used to model the instrument PSF

⬅ 1-d PSF of HARPS as retrieved through Gaussian Process regression on LFC spectra. HARPERFECT is generalizing the approach to 2 dimensions, using CNNs.



⬆ Screenshoot of Astrocook, a GUI Python package for spectral analysis

What next?

HARPERFECT will be the basis for a pluggable spectro-perfectionist module to be adapted to other instruments like **HARPS-N@TNG** and **ESPRESSO@VLT**, and to be extended to the next-generation spectrographs, like **ANDES@ELT**, using state-of-the-art simulated data to investigate critical points.

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