Disentangling the Interplay of the Inner Region of AGNs via Probabilistic Photometry

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What are AGNs?

Galaxies that host a ***supermassive black hole*** (SMBH) in their central region, with mass $>10^8\ M_\odot$, and a high accretion rate are known as ***Active Galactic Nuclei (AGNs)***. The infalling matter onto the SMBH results in the transformation of gravitational potential energy into radiation, making AGNs the most luminous sources in the universe.

A thin ***accretion disk (AD)*** forms due to the conservation of angular momentum. Collisions within the disk heat it up depending on the distance to the SMBH, producing broad radiation across the electromagnetic spectrum. The ***Broad Line Region (BLR)*** is a dust-free region of clouds. Ionizing radiation from the AD reaches these clouds, producing high and low ionization emission lines (Fig. 1).

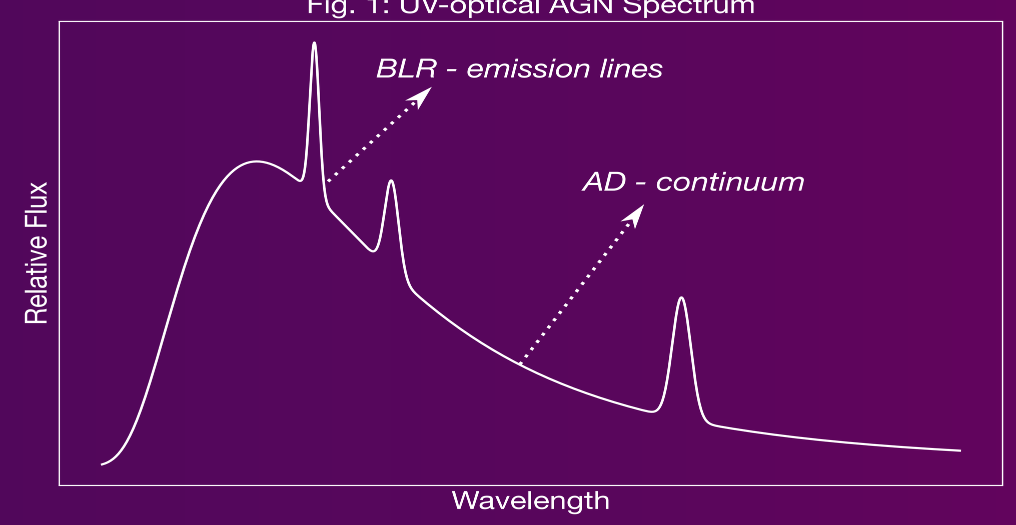
How does the AGN radiation change over time?

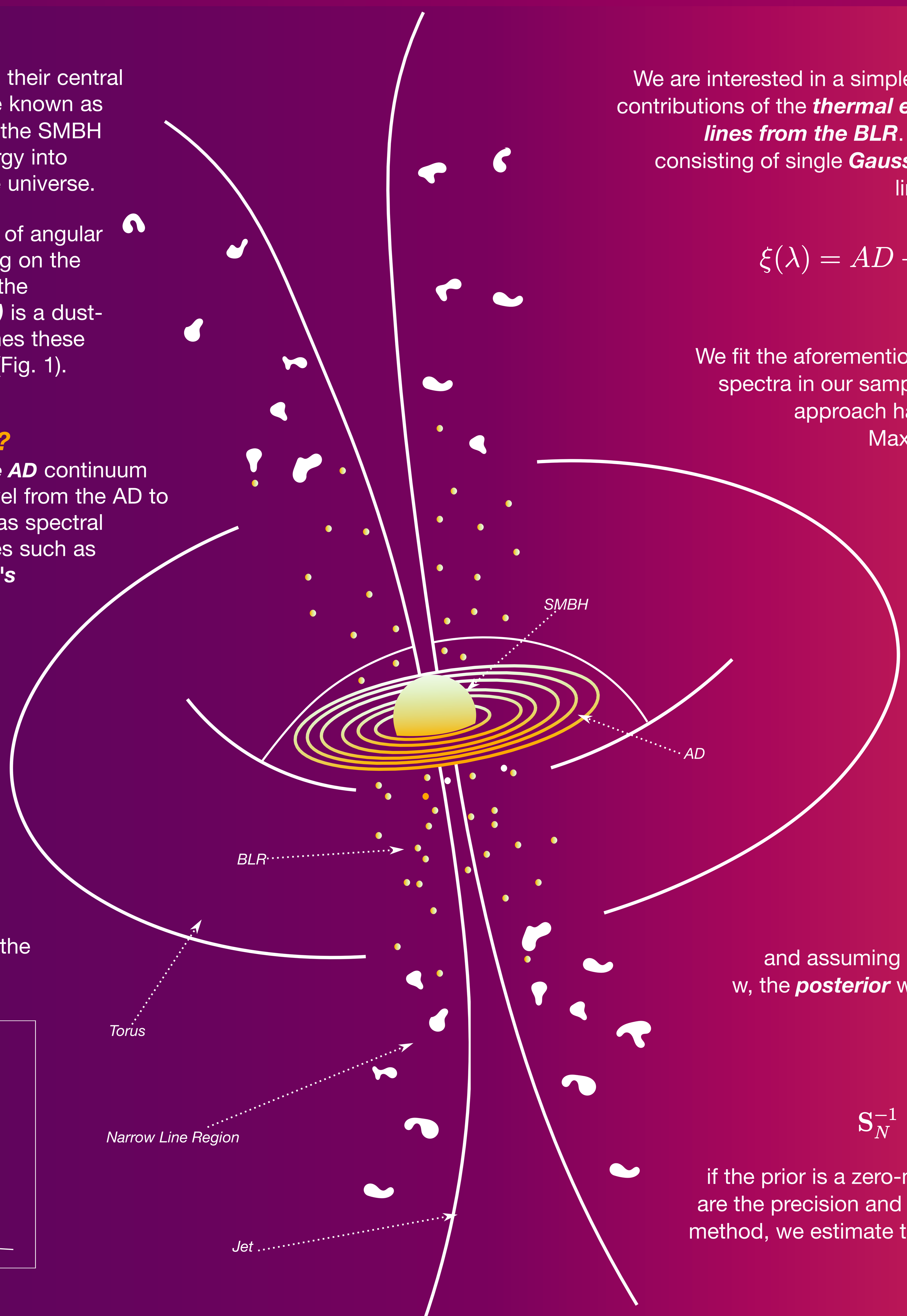
The emission from the ***BLR*** exhibits a ***delay relative to the AD*** continuum because of the time it takes for the ionizing energy to travel from the AD to the BLR clouds, ionize the gas, and re-emit the light as spectral lines. This time delay can be measured through techniques such as reverberation mapping and provides insight into the ***BLR's structure and dynamics***. However, this method requires significant resources, as spectral time series are needed.

Our approach

The aim of this work is to analyze the ***time lag*** of the BLR lines with respect to the AD continuum using ***multi-epoch photometry*** and ***single-epoch spectroscopy*** from the ***SDSS-Stripe 82*** catalog. The main challenge is that the fraction of the observed flux originating in the BLR at any given time is unknown, as AGNs are variable sources. To address this, we first test a simple spectral model to estimate this fraction from the observed single-epoch spectrum and then use this information to analyze the photometric time series.

Fig. 1: UV-optical AGN Spectrum





The Naive Spectral Model

We are interested in a simple model that allows us to disentangle the contributions of the ***thermal emission from the AD*** and the ***emission lines from the BLR***. Therefore, we consider a spectral model consisting of single ***Gaussian functions*** to represent the emission lines, and a ***power-law*** as the continuum:

$$\xi(\lambda) = AD + BLR = b \cdot \lambda^{-\gamma} + \sum_{i=1}^{M} w_i \cdot \phi_i(\lambda)$$

Bayesian Linear Regression

We fit the aforementioned ***spectral model*** to the single-epoch spectra in our sample using Bayesian linear regression. This approach has an advantage over other methods like Maximum Likelihood Estimation, as it avoids overfitting while being computationally efficient. This method assumes that the model is a ***linear combination of nonlinear*** given ***basis functions*** of the input variables:

$$y(\mathbf{x}, \mathbf{w}) = \sum_{j=0}^{M} w_j f_j(\mathbf{x}) = \mathbf{w}^T \mathbf{f}(\mathbf{x})$$

Considering the ***target*** variables, with Gaussian noise ϵ, as:

$$t = y(\mathbf{x}, \mathbf{w}) + \epsilon$$

the ***likelihood*** is given by

$$p(\mathbf{t}|\mathbf{x}, \mathbf{w}) = \prod_{n=1}^{N} \mathcal{N}\left(t_n | \mathbf{w}^T f(x_n), \beta^{-1}\right)$$

and assuming a ***prior distribution*** over the parameters w, the ***posterior*** will be a Gaussian distribution of the form

$$p(\mathbf{w}|\mathbf{t}) = \mathcal{N}(\mathbf{w}|\mathbf{m}_N, \mathbf{S}_N)$$

with ***covariance*** and ***mean***:

$$\mathbf{S}_N^{-1} = \alpha \mathbf{I} + \beta \mathbf{f}^T \mathbf{t} \qquad \mathbf{m}_N = \beta \mathbf{S}_N \mathbf{f}^T \mathbf{t}$$

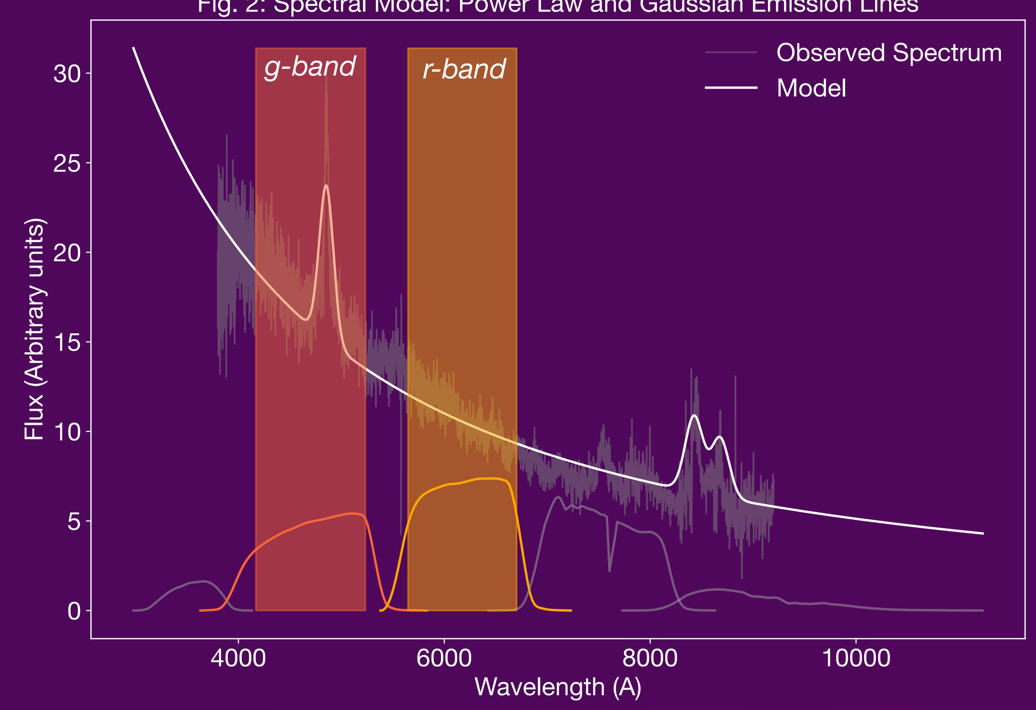
if the prior is a zero-mean isotropic Gaussian, alpha and beta are the precision and noise parameters, respectively. With this method, we estimate the ***spectral parameters*** in each source.

The BLR emission

After getting the spectral parameters through Bayesian linear regression, we calculate the flux belonging to the ***BLR in the photometric measurements***. For this, we folded the probabilistic model with the ***SDSS ugriz*** transmission curves. Consider an example for a specific source at redshift 0.73, where the observed Mg II spectral line falls within the wavelength range of the g-filter (Fig. 2), while the flux in the r-filter comes exclusively from the continuum:

$$F_g = \text{Mg II} + \text{Cont}_g \qquad F_r = \text{Cont}_r$$

Fig. 2: Spectral Model: Power Law and Gaussian Emission Lines

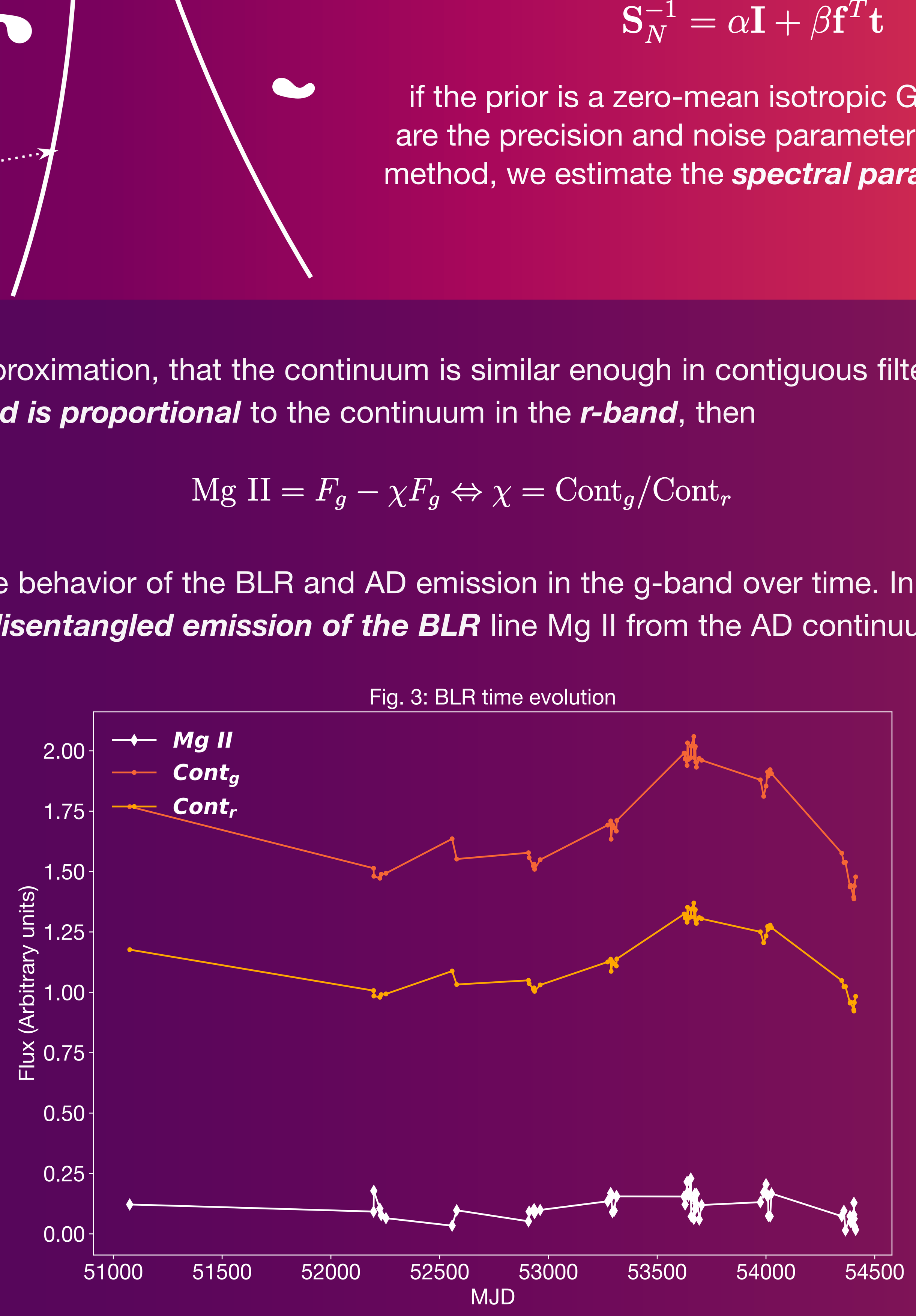


Assuming, as a first approximation, that the continuum is similar enough in contiguous filters, such that the continuum in the ***g-band is proportional*** to the continuum in the ***r-band***, then

$$\text{Mg II} = F_g - \chi F_g \Leftrightarrow \chi = \text{Cont}_g / \text{Cont}_r$$

We can then retrieve the behavior of the BLR and AD emission in the g-band over time. In the Figure 3 we show the time series for the ***disentangled emission of the BLR*** line Mg II from the AD continuum in bands g and r.

Fig. 3: BLR time evolution



The next challenge

Calculating the lag between emissions is not a trivial task, and the modeling becomes increasingly complex if we account for temporal changes in the ratio of the continuum between both filters. The next step in this project is to account for these changes and implement a ***temporal spectral model*** through a ***Gaussian Process*** to model the ***latent activity*** driving the AGN optical flux.

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