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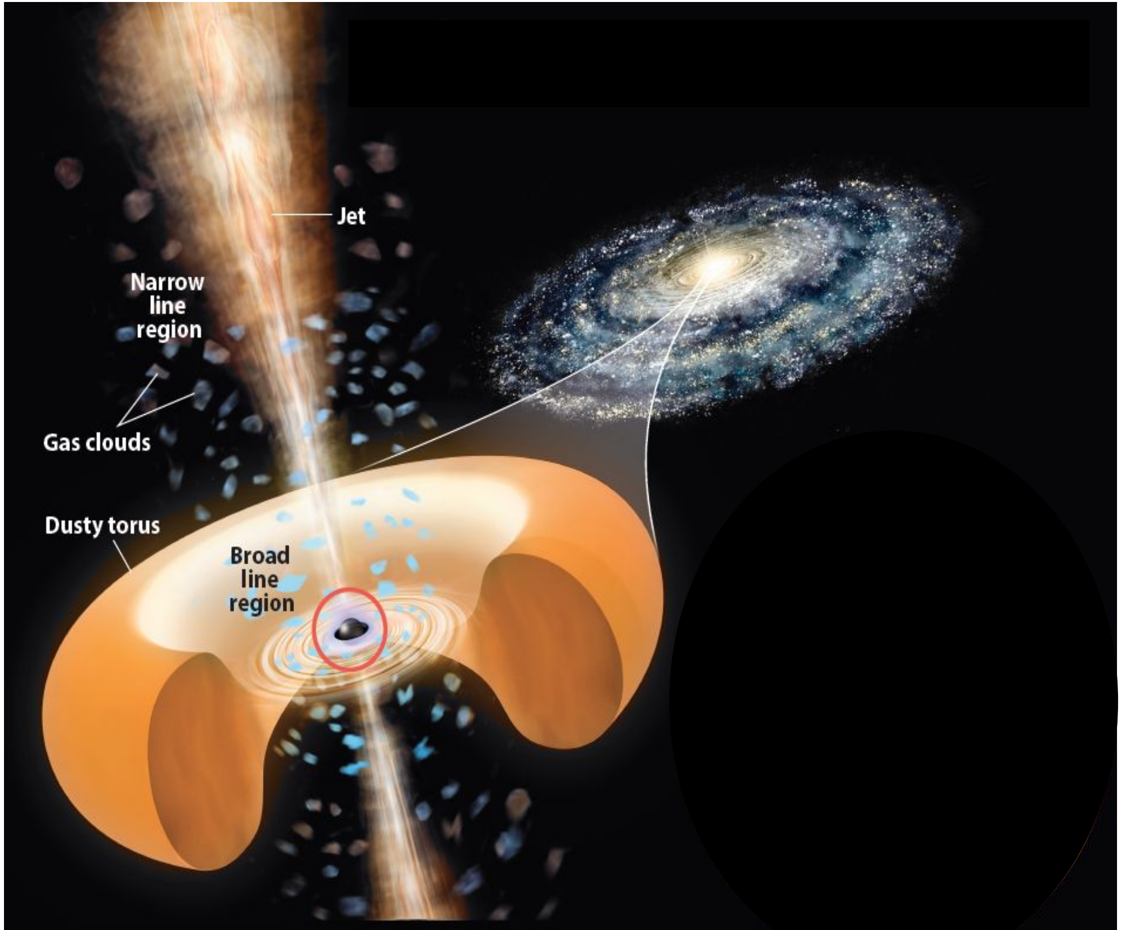
The observational quest for Massive Black Hole Binaries

Fabio Rigamonti

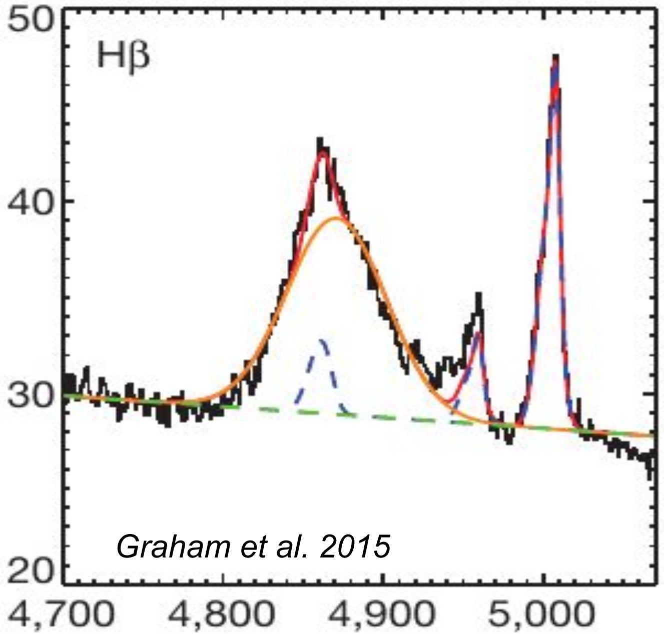
S. Covino, P. Severgnini, M. Dotti, M. Landoni, Singh J., Bertassi L., Sottocorno E., Braito V., Cicone C., Vignali C., De Rosa A., Ighina L., Caccianiga A.

Credits: ligo/caltec/MIT/sonoma state

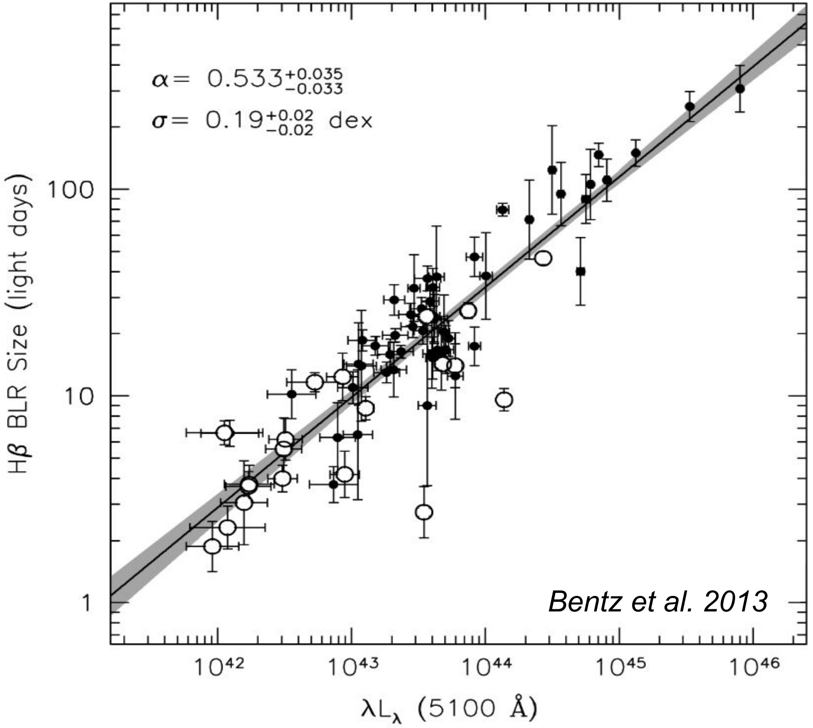
Introduction: AGN structure



Introduction: AGN structure



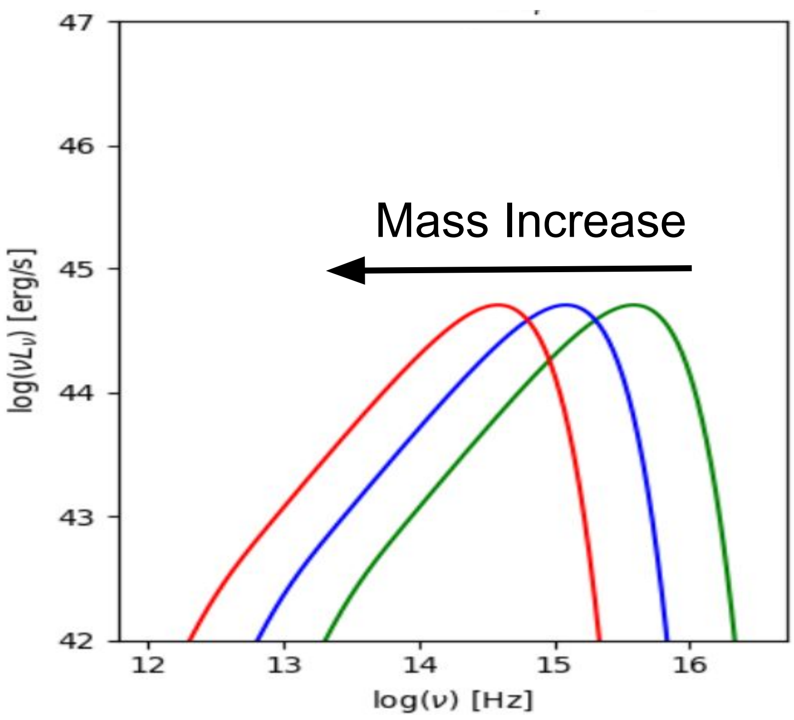
$$R_{\mathrm{B-H}\beta} \approx 11\,\mathrm{light\,day} \times \left(f_{\mathrm{Edd}} \frac{M}{10^6\, M_\odot} \right)^{0.519}$$

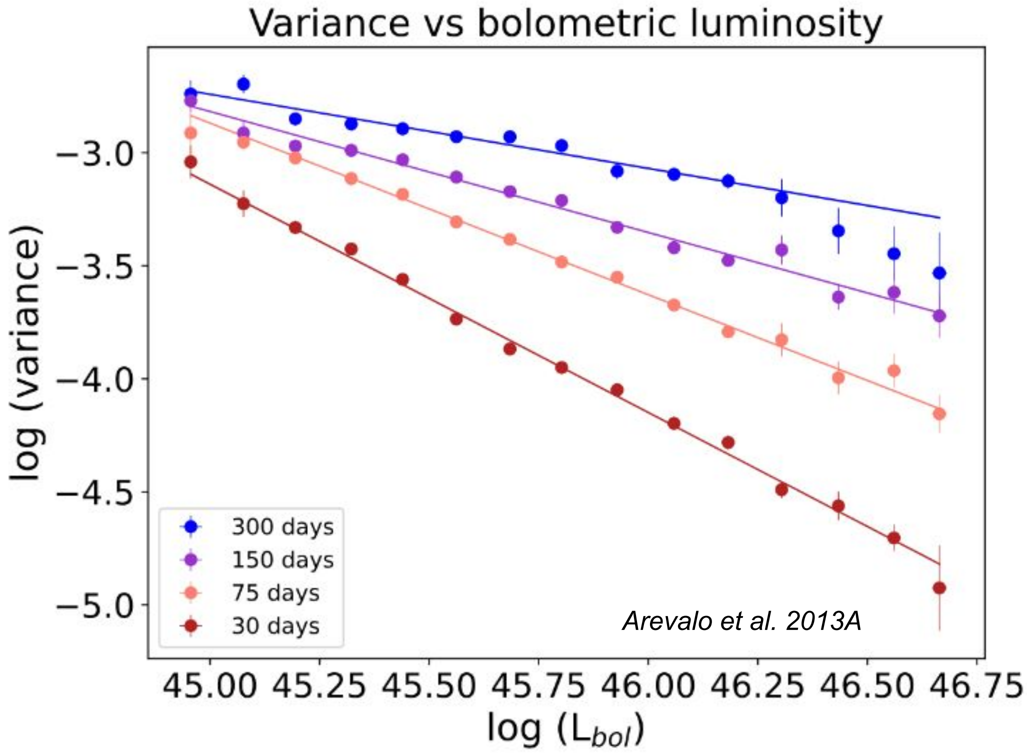


$$R_{B-\mathrm{H}\beta} \simeq 36\ ld \simeq 0.03\ pc$$

$$\mathrm{FWHM}_{\mathrm{B-H}\beta} \simeq 3500\ \mathrm{km/s}$$

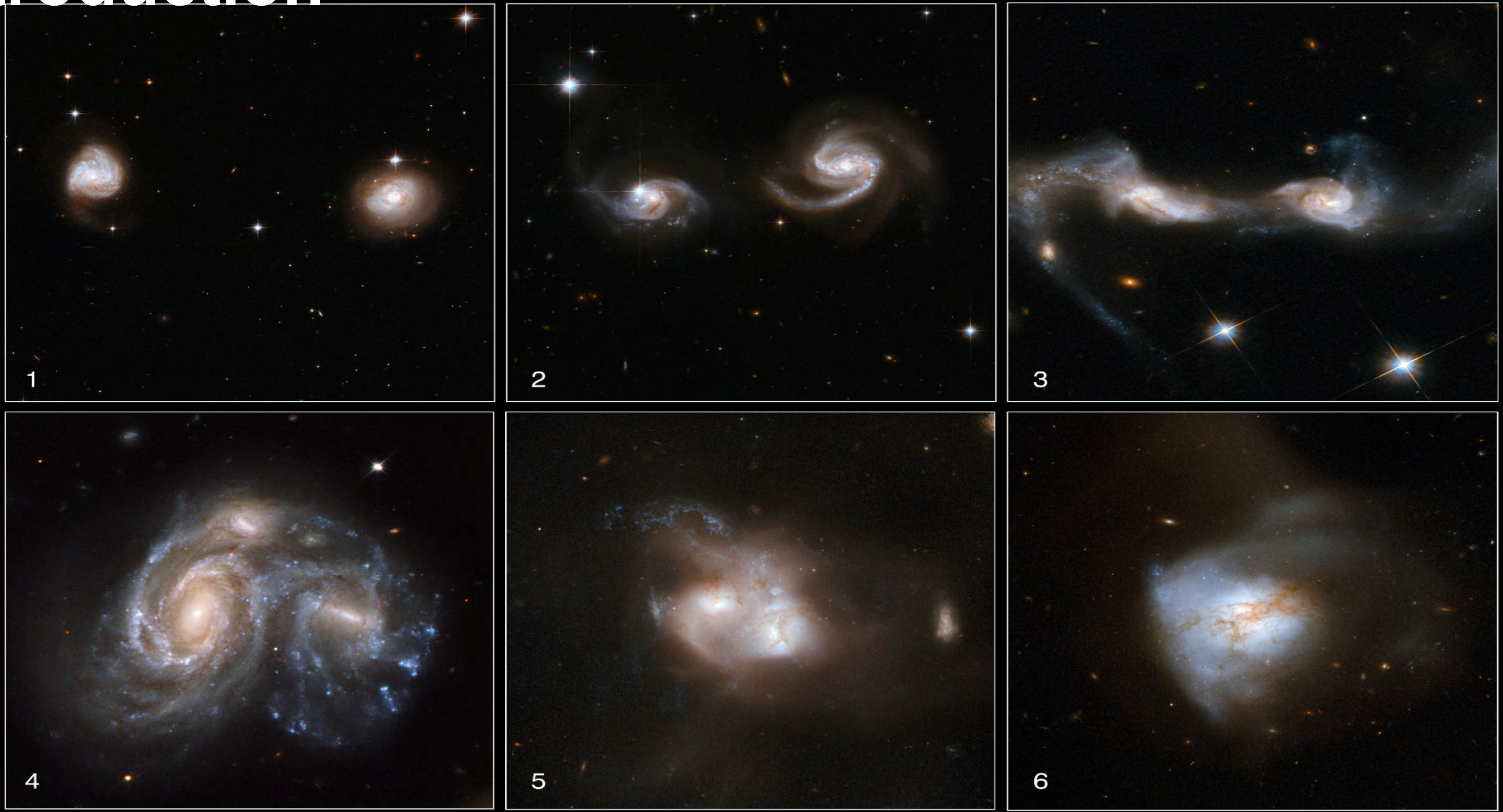
Introduction: AGN structure



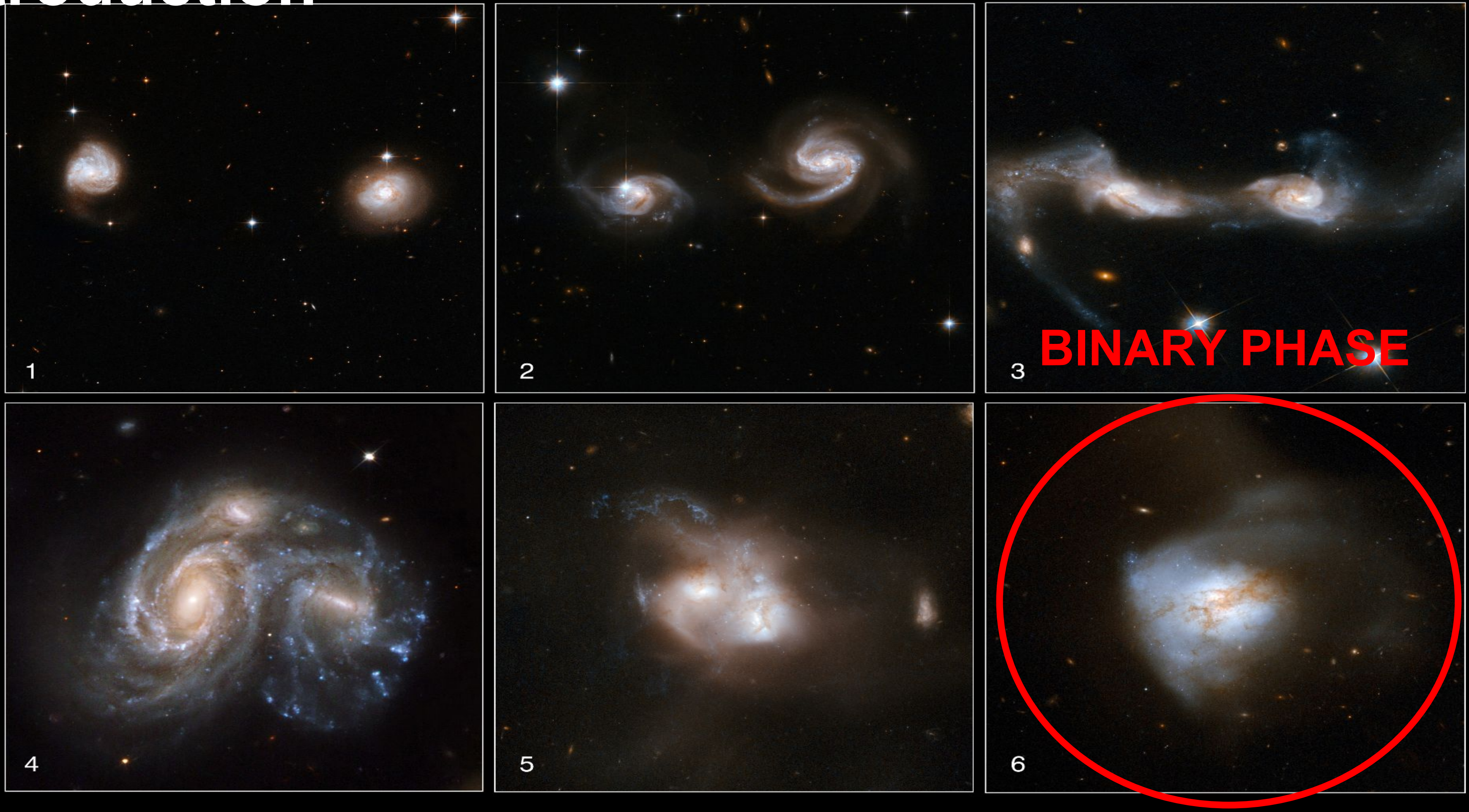


$$\log \text{variance} = -0.33 \times (\log L_{bol} - 45.8) - 3.01 \qquad \text{timescale} \sim 300d$$

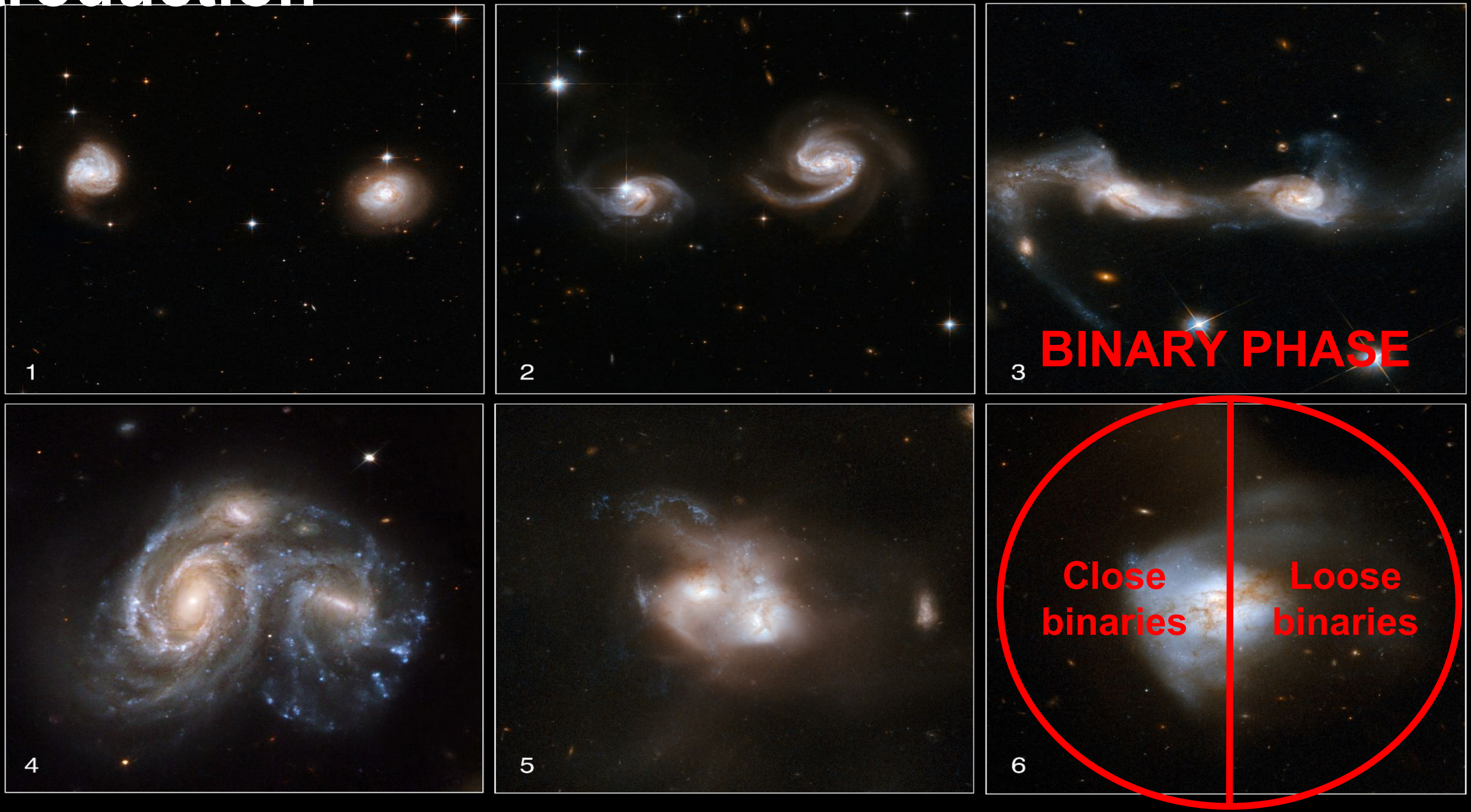
Introduction



Introduction

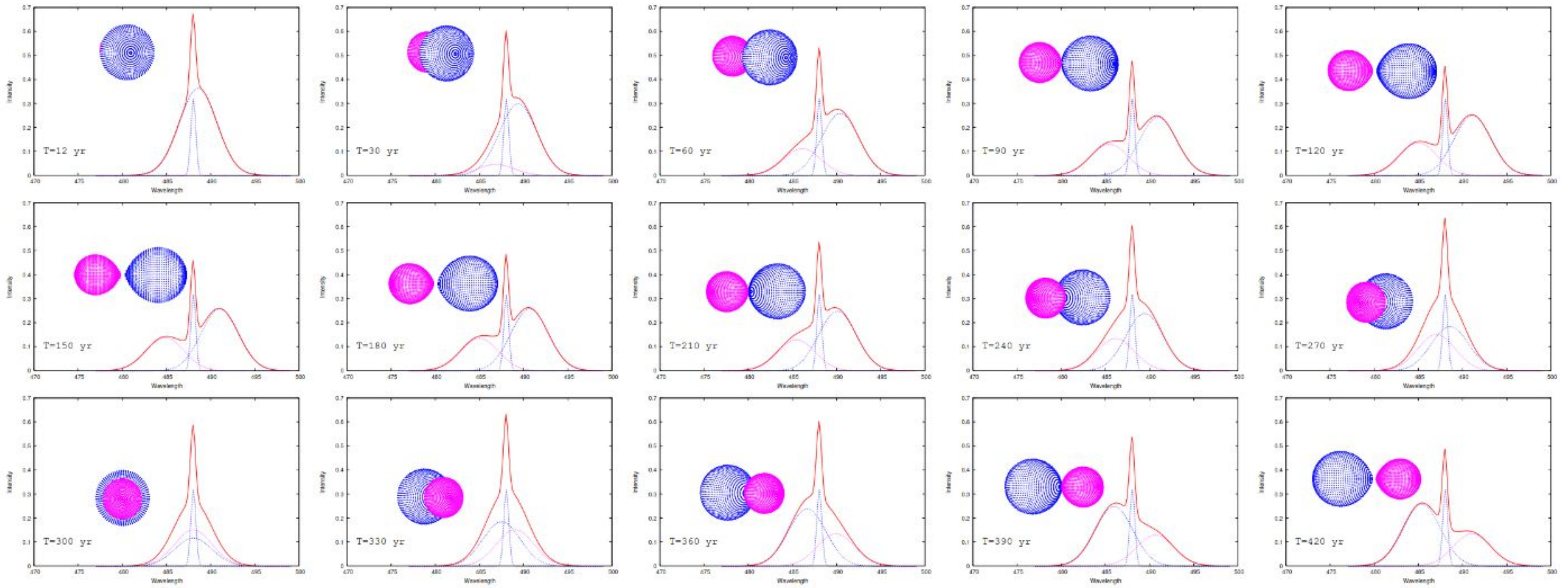


Introduction



Spectroscopy: loose binaries

Peculiar spectral properties of the broad lines in optical/UV spectra



Popović et al. 2012

Spectroscopy: loose binaries

Peculiar spectral properties of the broad lines in optical/UV spectra

Not binary-unique!

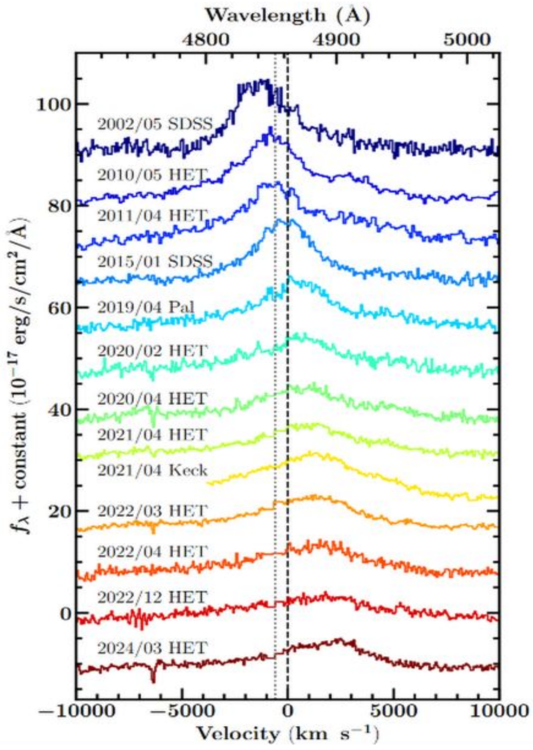
- Superposition
- Recoiling BH
- Eccentric BLR
- Distrubed BLR
- Partial Obscuration

Spectroscopy: loose binaries

Peculiar spectral properties of the broad lines in optical/UV spectra

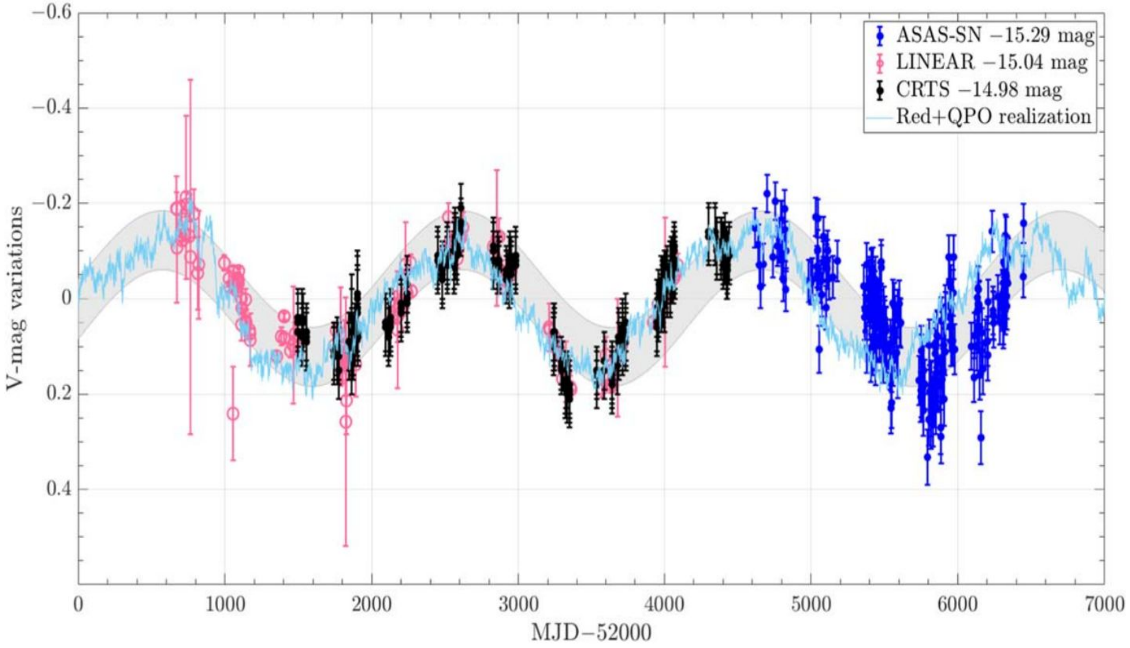
- Superposition
- Recoiling BH
- Eccentric BLR
- Distrubed BLR
- Partial Obscuration

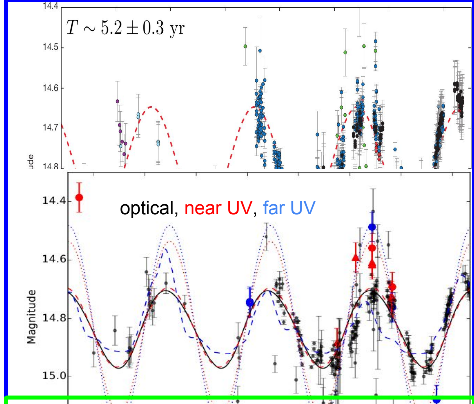
1 good candidate

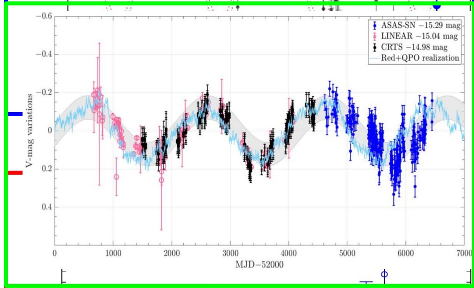


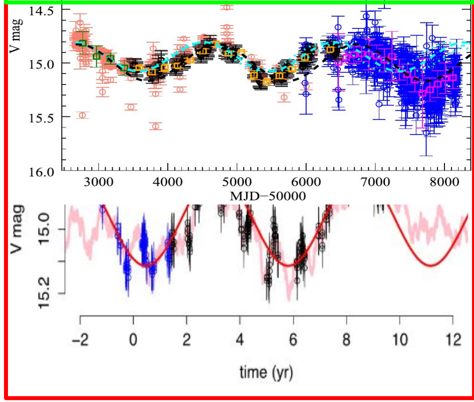
J0950+5128, Mohammed et al. 2025

Spectroscopy: PG 1302-102



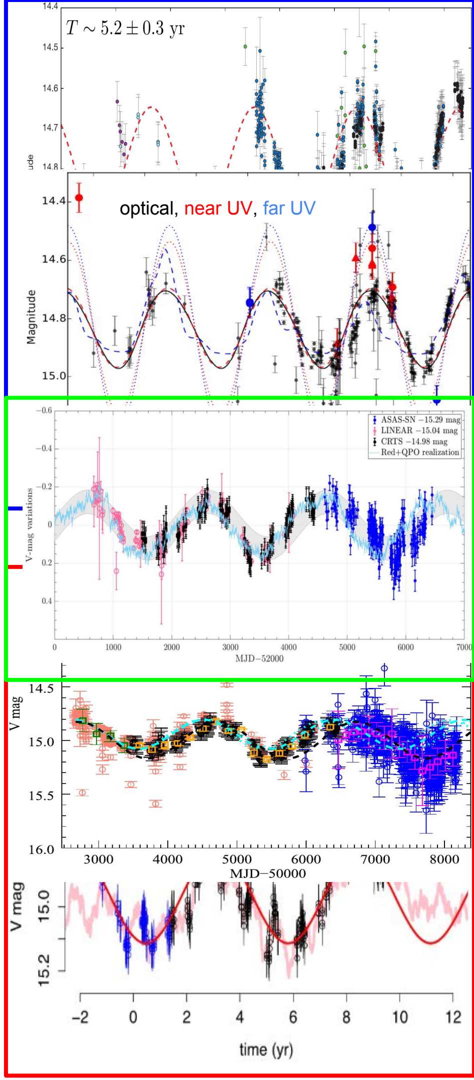






Spectroscopy: PG 1302-102

Can we use high resolution optical spectroscopy to better understand the nature of PG 1302-102?



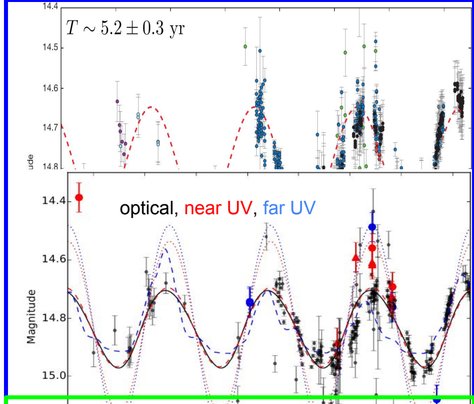
Spectroscopy: PG 1302-102

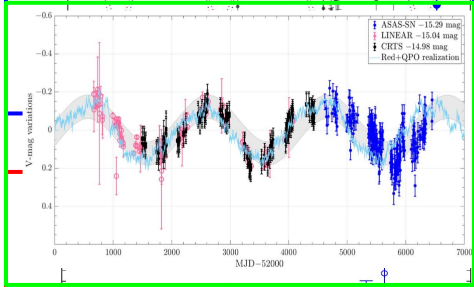
Can we use high resolution optical spectroscopy to better understand the nature of PG 1302-102?

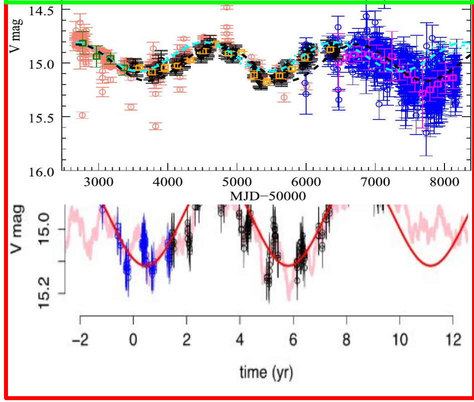
High resolution data with **ESPRESSO**@VLT

+

Bayesian analysis of the spectrum

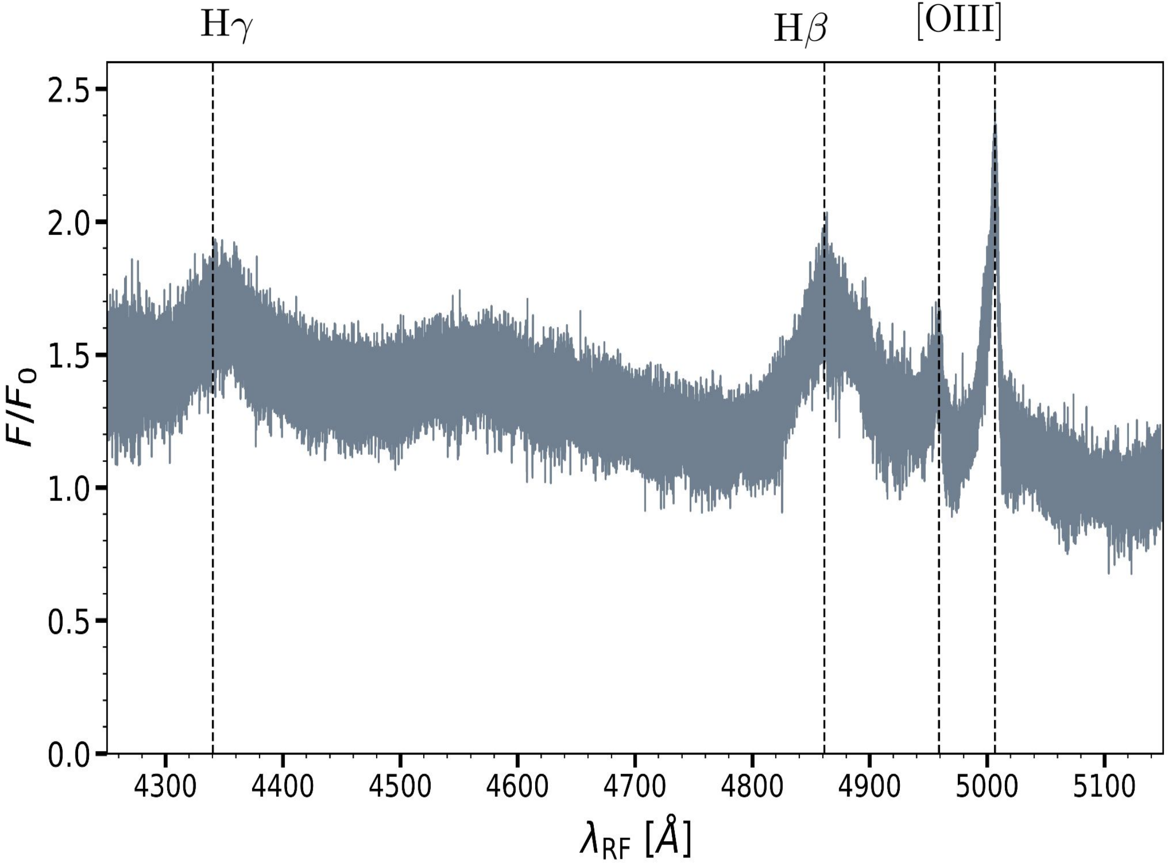






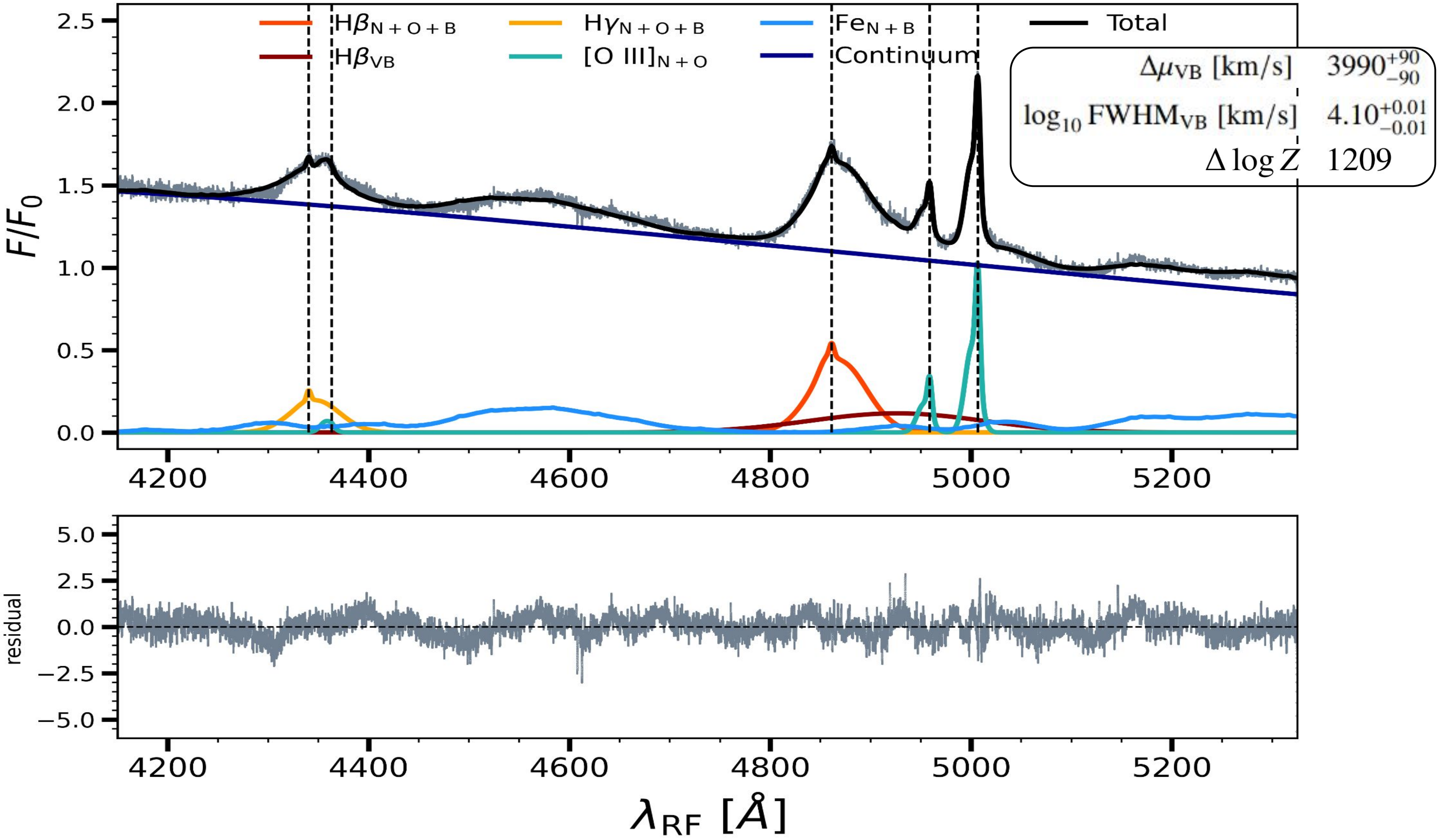
Spectroscopy: PG 1302-102

- Gaussian for **narrow** emission lines
- Gaussian for **broad** emission lines
- Gaussian for “**outflow**” emission
- Power law **continuum**
- **Iron** contribution (multiple narrow and broad Gaussian *Véron-Cetty 2004*)



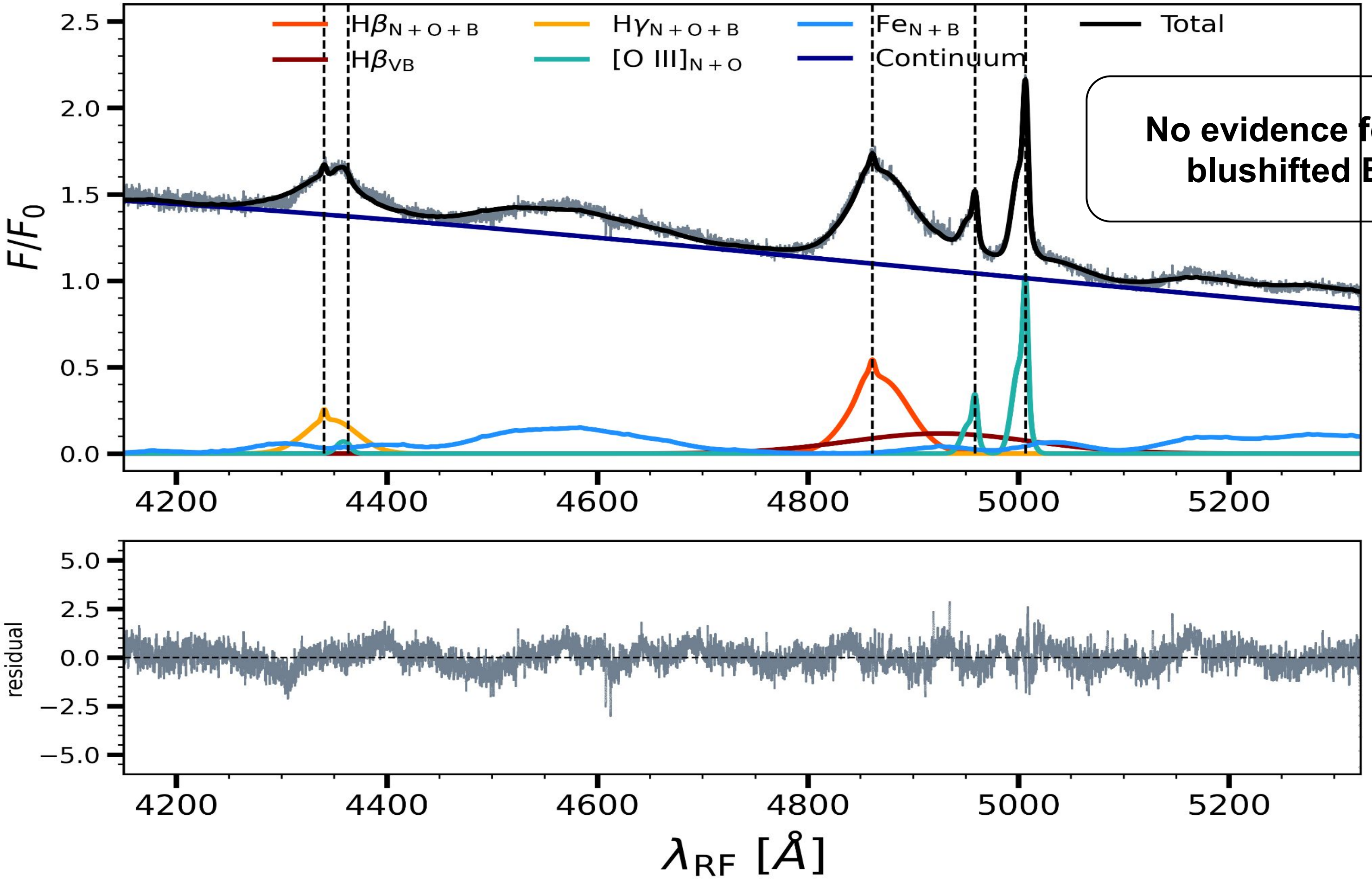
Spectroscopy: PG 1302-102

Rigamonti et al. 2025



Spectroscopy: PG 1302-102

Rigamonti et al. 2025



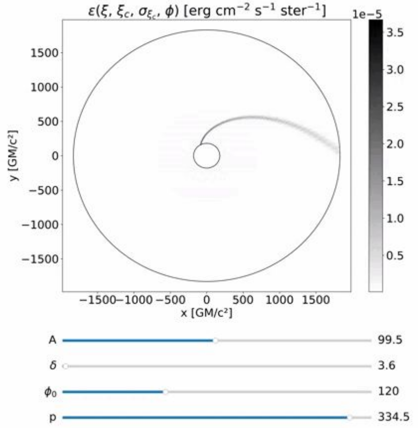
No evidence for any blushifted BLR

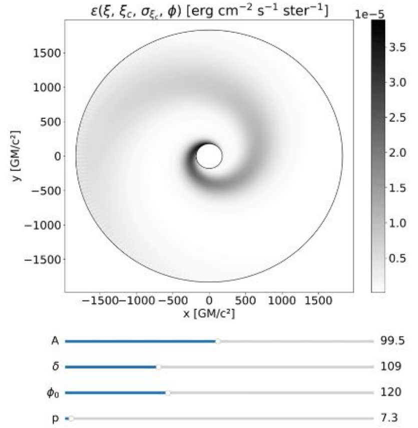
Spectroscopy: PG 1302-102

Rigamonti et al. 2025

$$\epsilon(\xi,\phi) = \xi^{-1} \cdot \exp\left[-\frac{(\xi-\xi_c)^2}{2\sigma_{\xi_c}^2}\right]\left\{1+ \frac{A}{2}\exp\left[-\frac{4\log 2}{\delta^2}(\phi-\psi_0)^2\right]+ \frac{A}{2}\exp\left[-\frac{4\log 2}{\delta^2}(2\pi-\phi+\psi_0)^2\right]\right\}$$

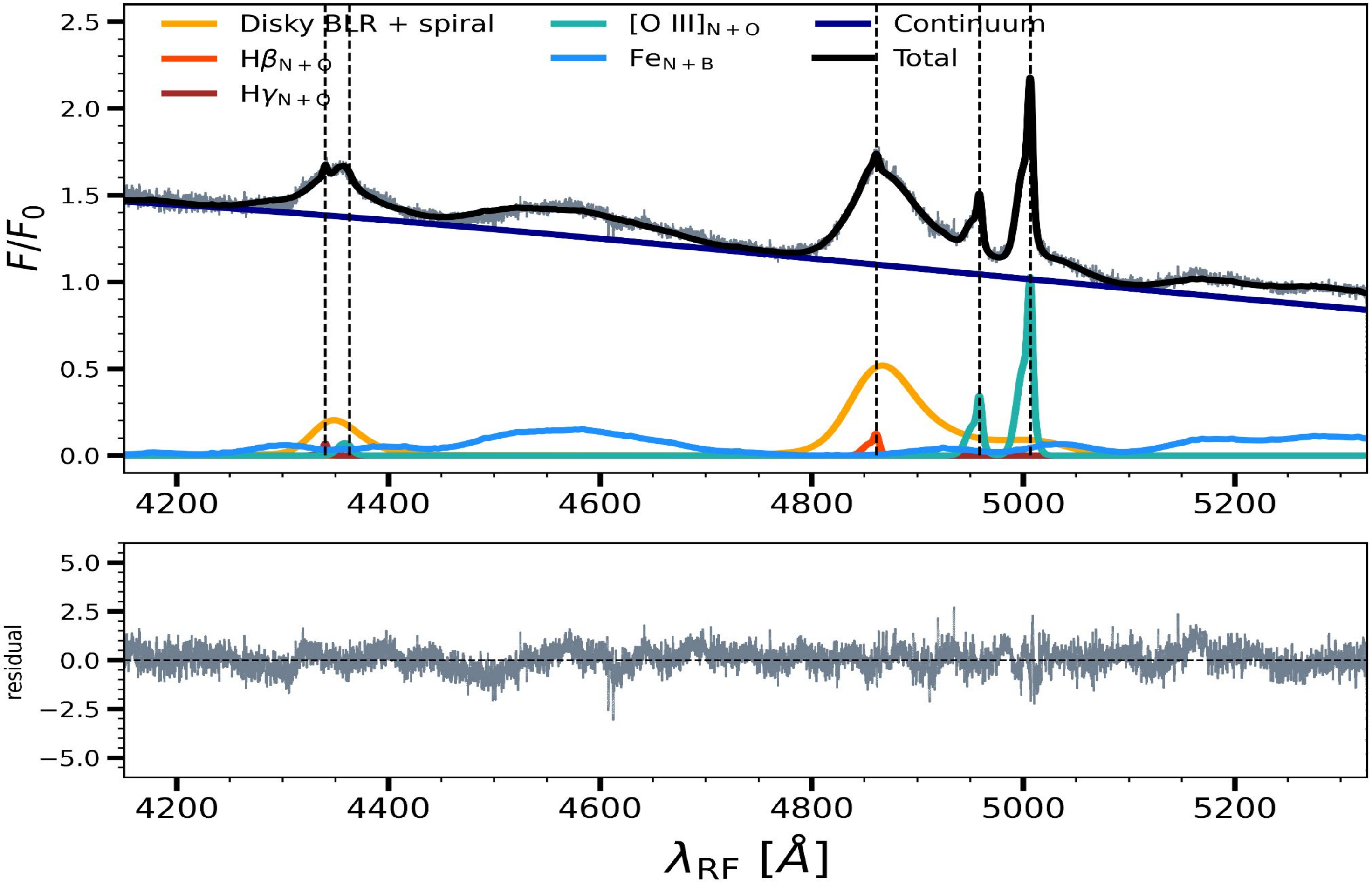
Sottocorno et al. in prep.



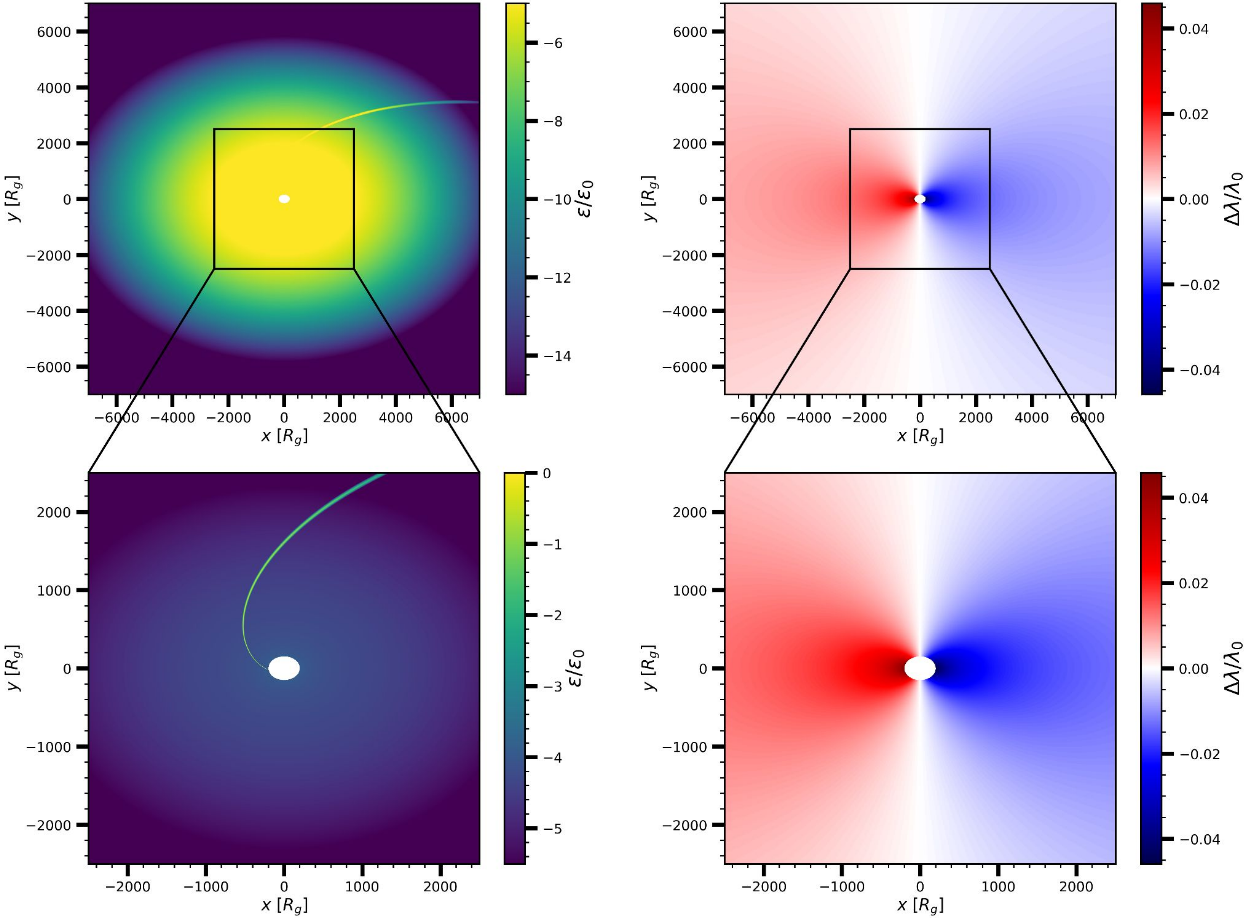


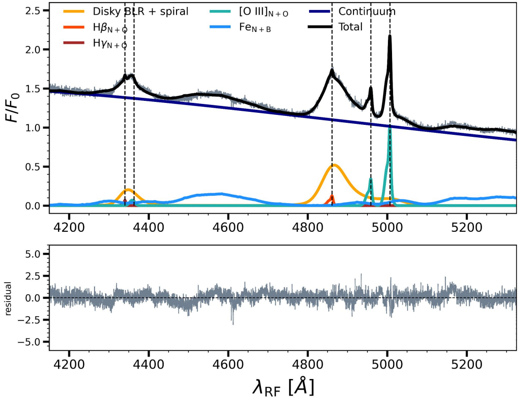
Spectroscopy: PG 1302-102

Rigamonti et al. 2025



Spectroscopy: PG 1302-102



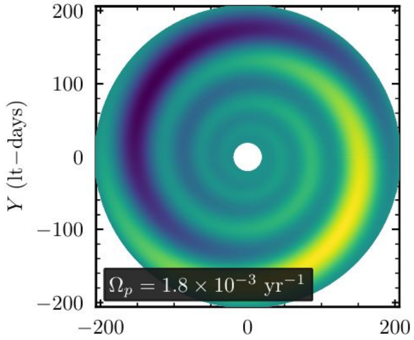


Spectroscopy: PG 1302-102

Rigamonti et al. 2025

If the BLR is truly disturbed, what is causing it?

- **Gravitational instabilities** in the outer part of AD



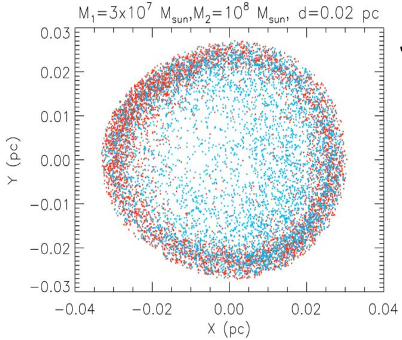
Wang et al. 2022

- **Ongoing merger** of two BLR

$\simeq$ 5.5yr period
mass $10^9\ M_\odot$
Circular motion

→ binary **separation** of $\simeq$ 0.015pc

Luminosity-radius → **BLR radius** $\simeq$ 250 lightdays $\simeq$ 0.2pc

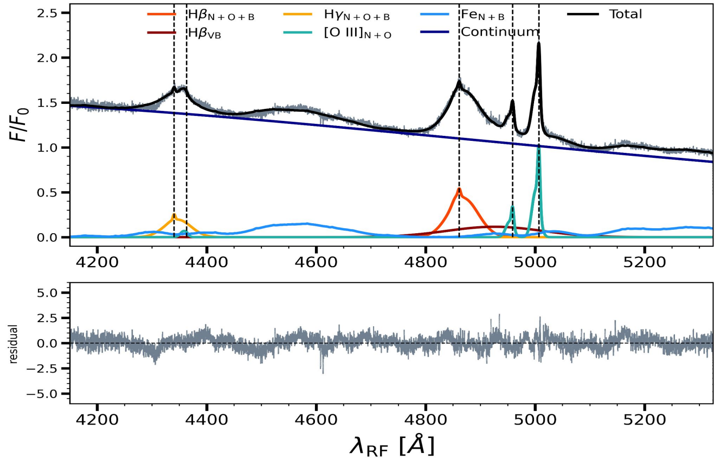


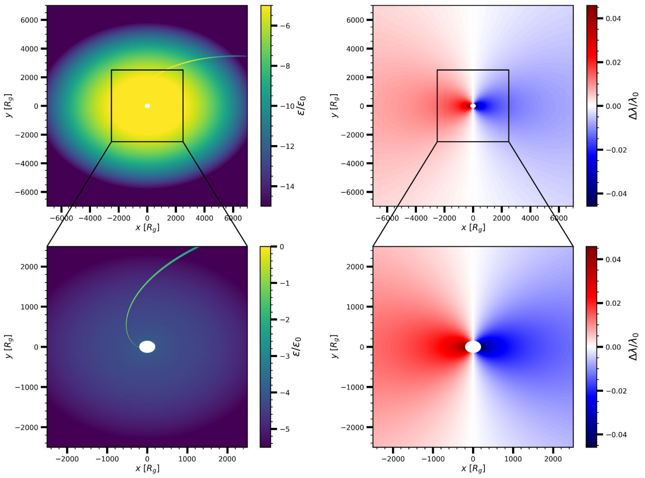
Shen et al. 2010

Conclusion n.1

Spectrum of PG 1302-102:

- **asymmetric redshifted emission** in broad lines
- **blueshifted outflow** in narrow line



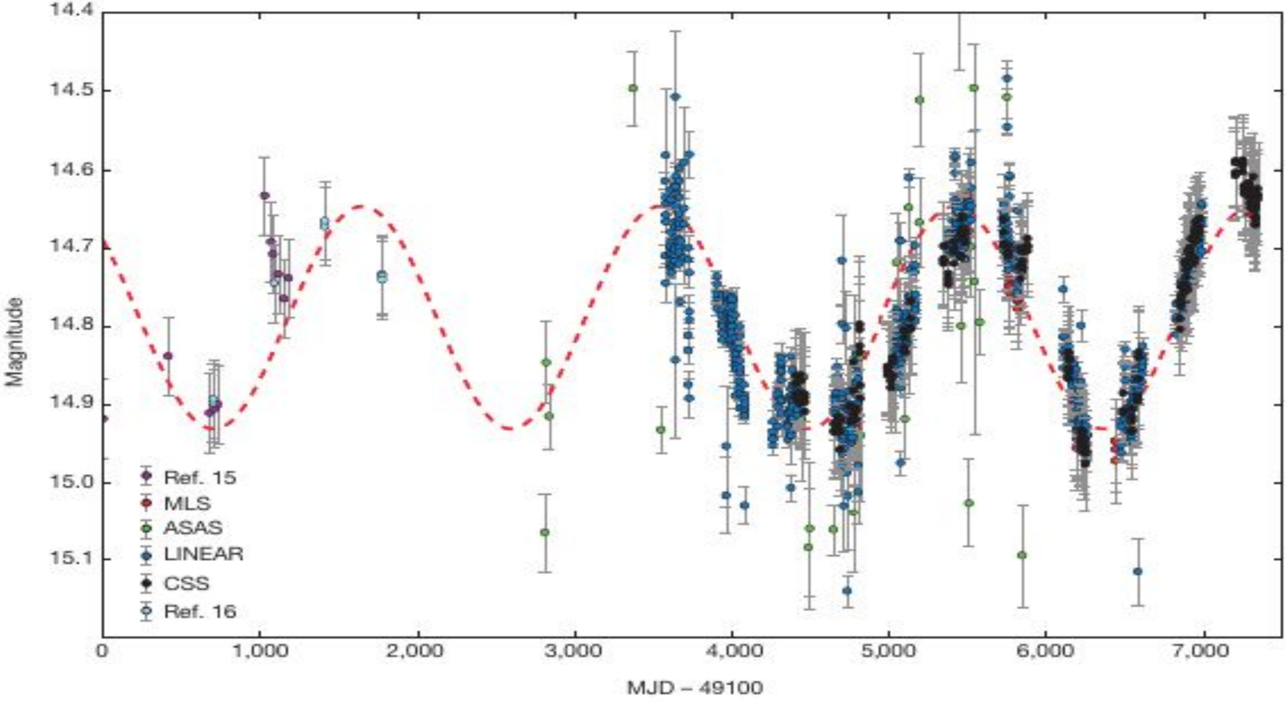


Evidence for **disturbed geometry** in the BLR:

- likely connected to **gravitational instabilities**
- **cannot** rule out **ongoing** merger

Time Domain: close binaries

(Quasi-)periodic variability of the continuum



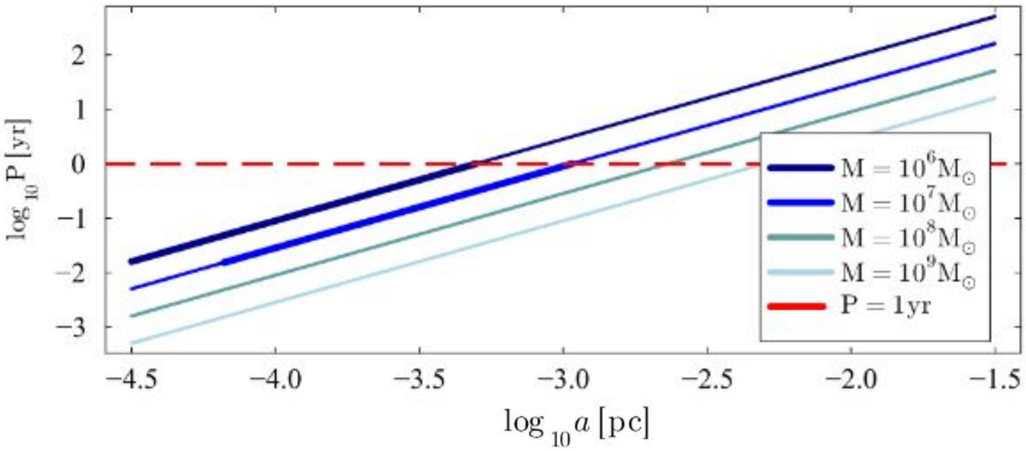
Graham et al. 2015

Time Domain: close binaries

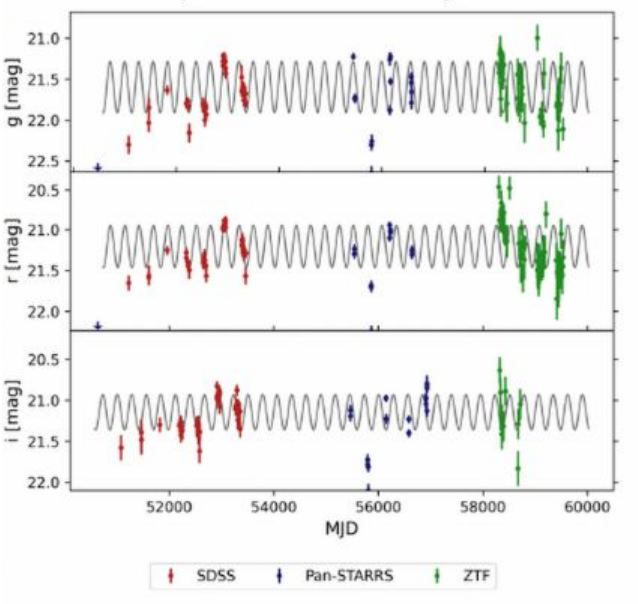
(Quasi-)periodic variability of the continuum

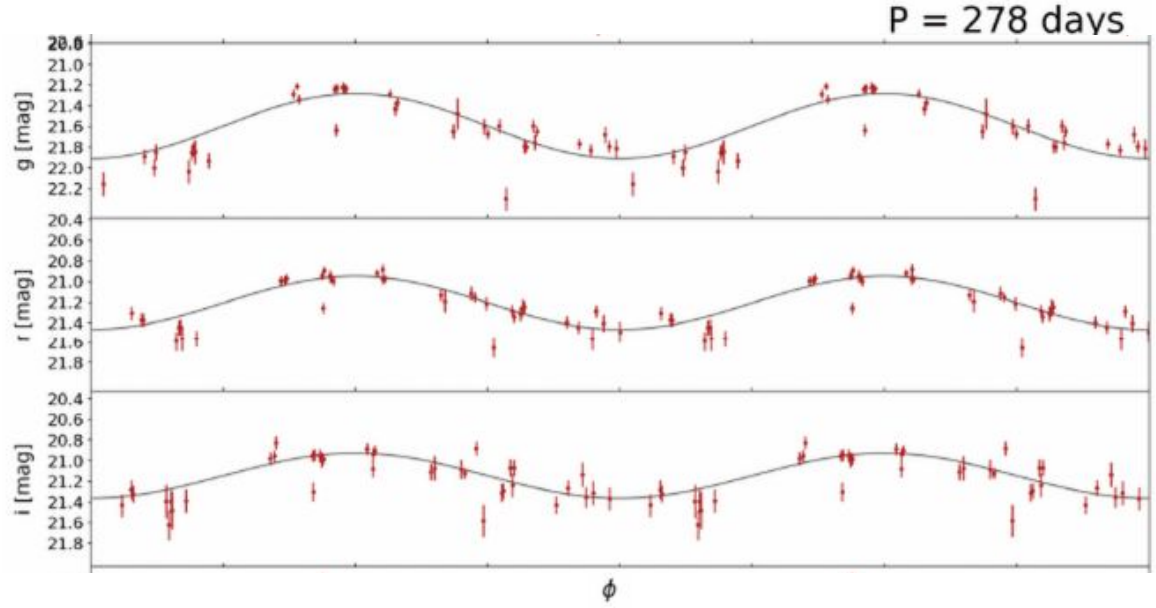
Not binary-unique!

- Random red noise (DRW)
- Precessing jets
- Precessing discs



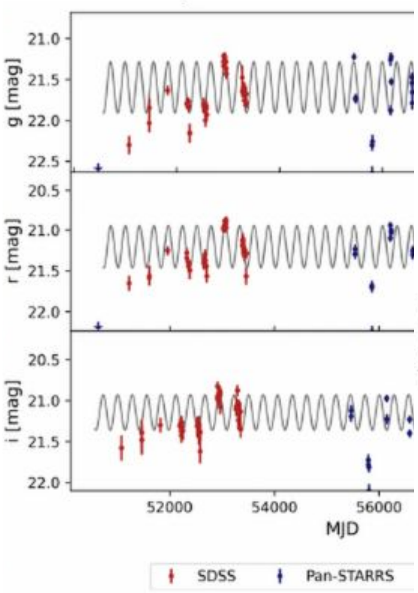
Time Domain: J2320+0024



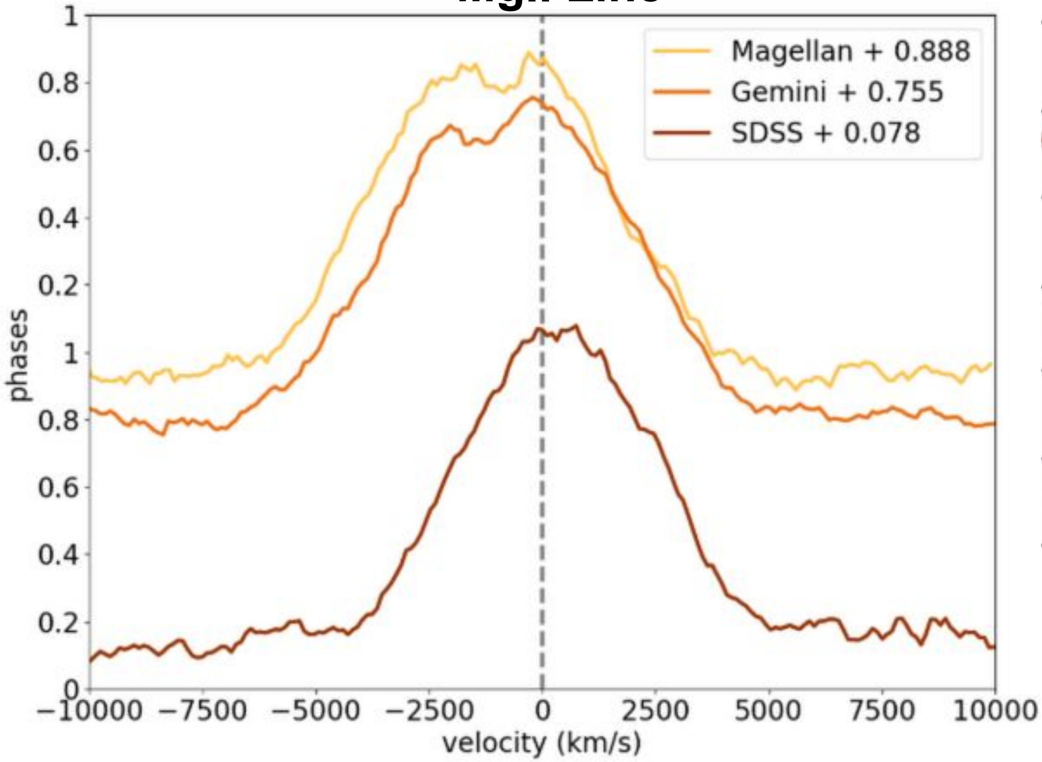


Fatovic et al. 2023

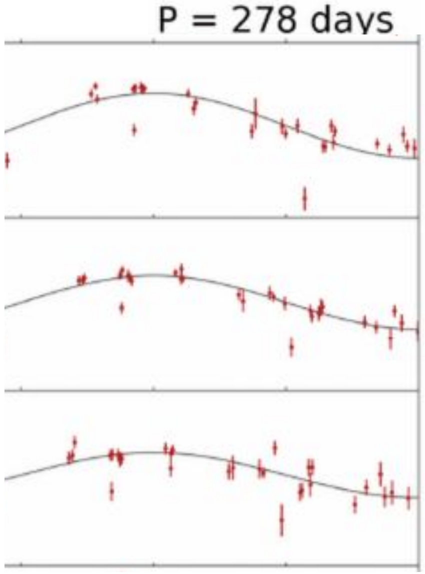
Time Domain: J2320+0024



MgII Line



Fatovic et al. 2025



Fatovic et al. 2023

Time Domain: J2320+0024

Lomb-Scargle periodograms struggle with non-sinusoidal supermassive BH binary signatures in quasar lightcurves

Allison Lin,[1] Maria Charisi,[2,3] and Zoltán Haiman[1,4,5]

ABSTRACT

Supermassive black hole binary (SMBHB) systems are expected to form as a consequence of galaxy mergers. At sub-parsec separations, SMBHBs are difficult to resolve, but can be identified as quasars with periodic variability. Previous periodicity searches have identified statistically significant candidates, but focused primarily on sinusoidal signals. However, theoretical models and hydrodynamical simulations predict that binaries produce more complex non-sinusoidal pulse shapes. Here we examine the efficacy of the Lomb-Scargle periodogram (LSP; one of the most popular tools for periodicity searches in unevenly sampled lightcurves) to detect periodicities with a saw-tooth shape mimicking results of hydrodynamical simulations. We simulate quasar lightcurves with damped random walk (DRW) variability and inject periodic signals. Our mock sample of 12,400 quasars consists either of idealised well-sampled lightcurves, or mimics the data in the Palomar Transient Factory (PTF) analyzed in Charisi et al. (2016). We assess the statistical significance of recovering two types of periodic signals, i.e. with sinusoidal and sawtooth pulse shapes. We find that the LSP detects 39.1% and 28.1% of the sinusoidal signals, in the PTF-like and idealised lightcurves, respectively. The fraction is significantly reduced for sawtooth periodicity, with only 7.5% and 1.1% detected in PTF-like and idealised lightcurves, respectively. These low recovery rates imply that previous searches have missed the large majority of binaries. Therefore, significant improvements are required beyond simple LSPs to successfully uncover SMBHBs in upcoming time-domain surveys.

Time Domain: J2320+0024

But, how many false periodic light curves the LSP give?

Lomb-Scargle periodograms struggle with non-sinusoidal supermassive BH binary signatures in quasar lightcurves

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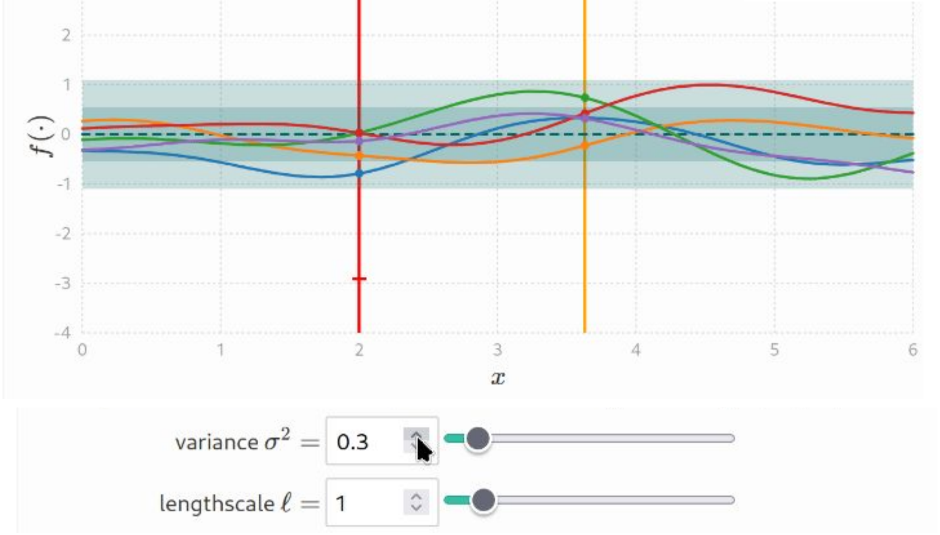
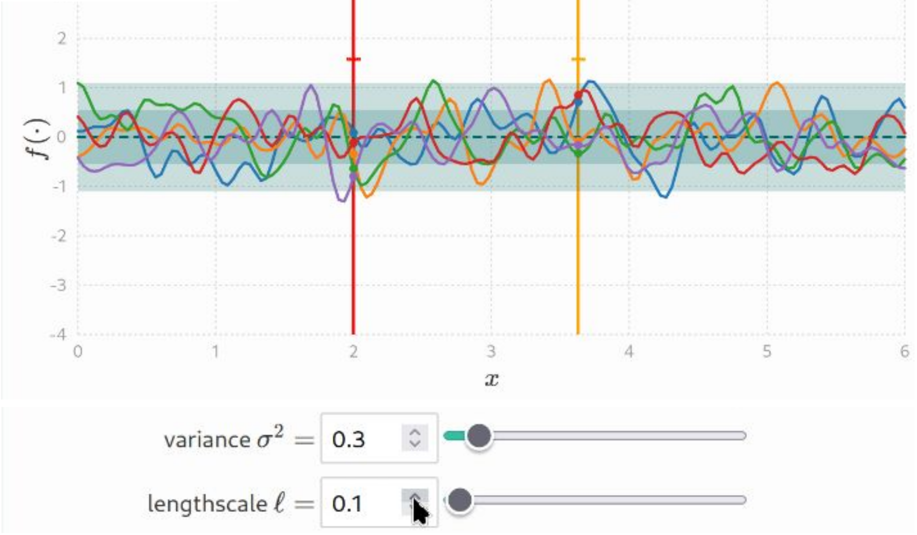
Time Domain: J2320+0024

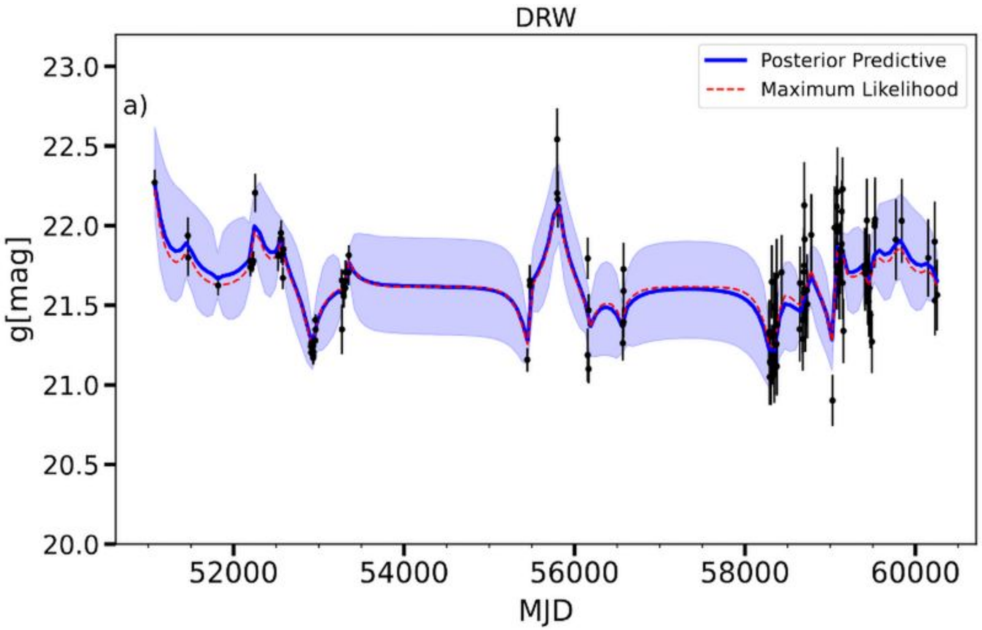
We do not care because **Gaussian Processes** are better (*Bertassi et al. in prep*)

$$\Sigma_{ij} = \frac{1}{2}\sigma^2\tau \exp\left(-\frac{|t_i - t_j|}{\tau}\right)$$

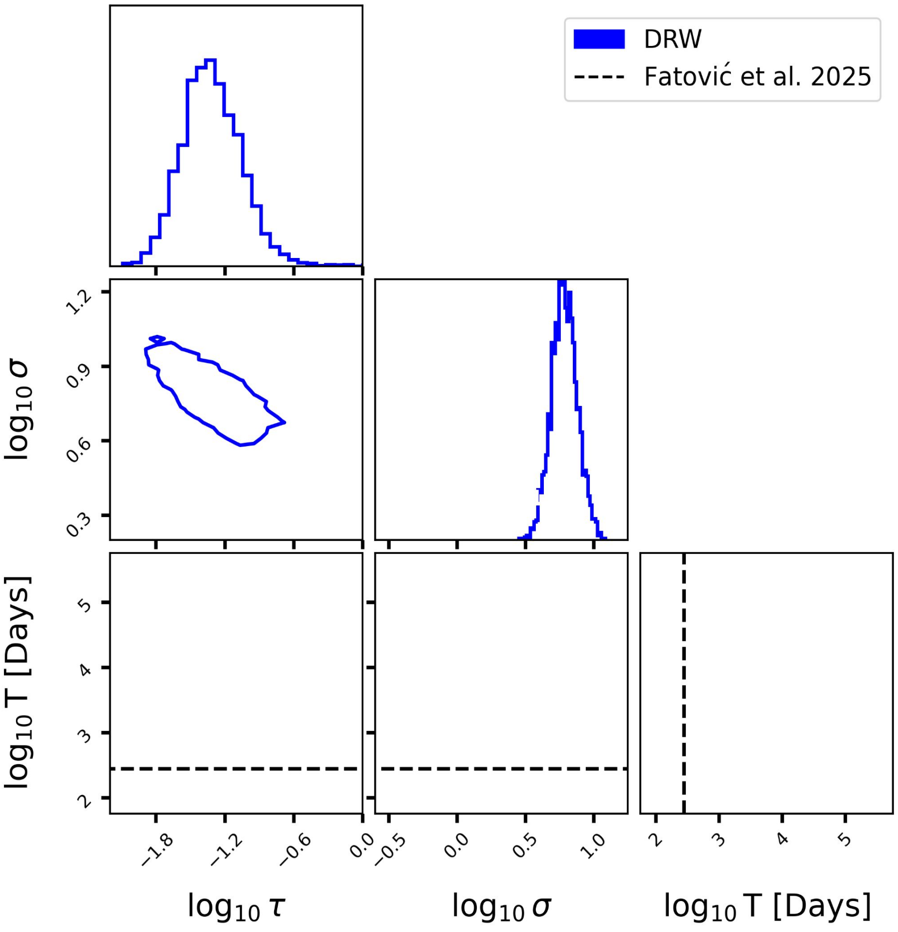




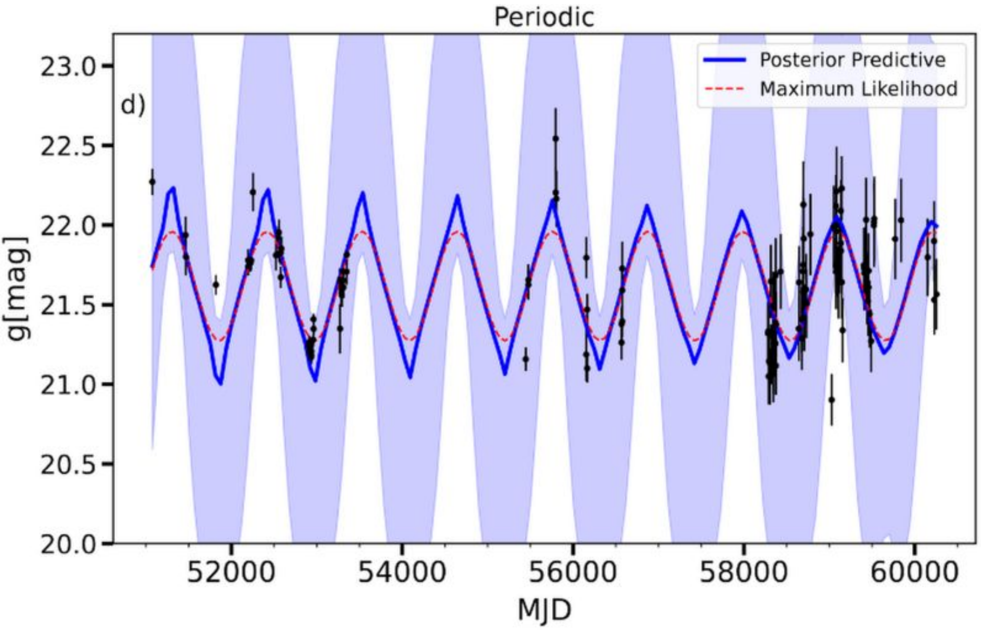
Time Domain: J2320+0024



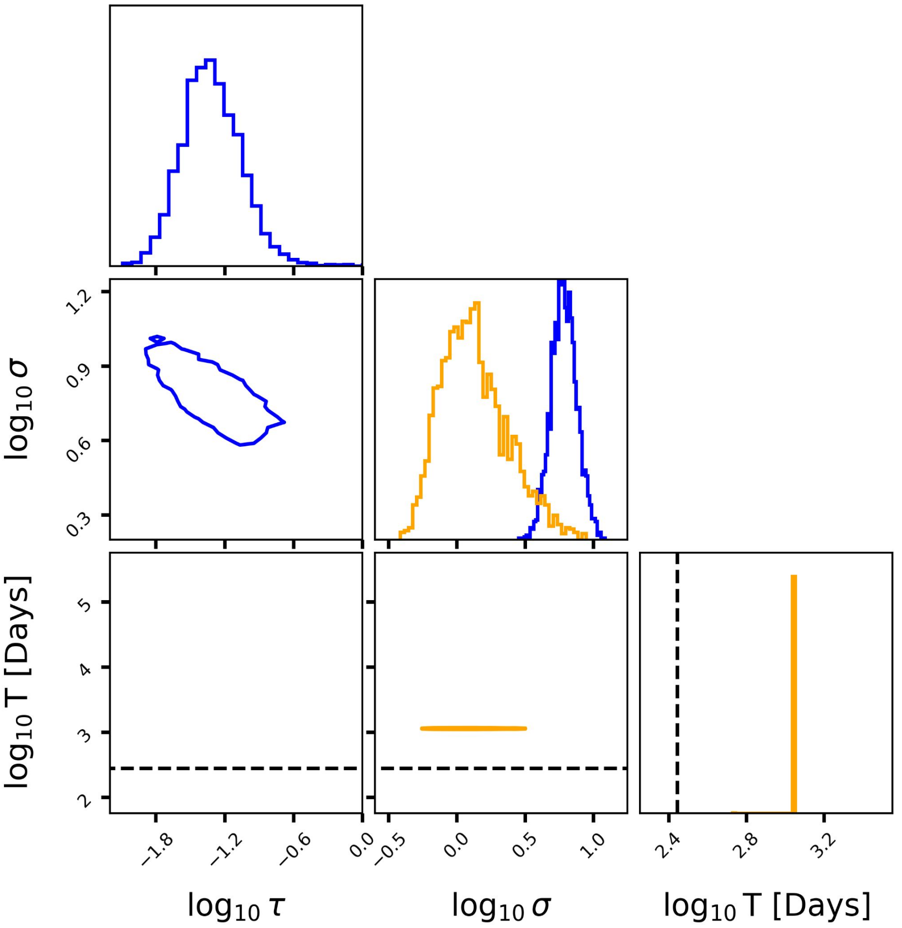
DRW $$\Sigma_{ij} = \frac{1}{2}\sigma^2\tau \exp\left(-\frac{|t_i - t_j|}{\tau}\right)$$



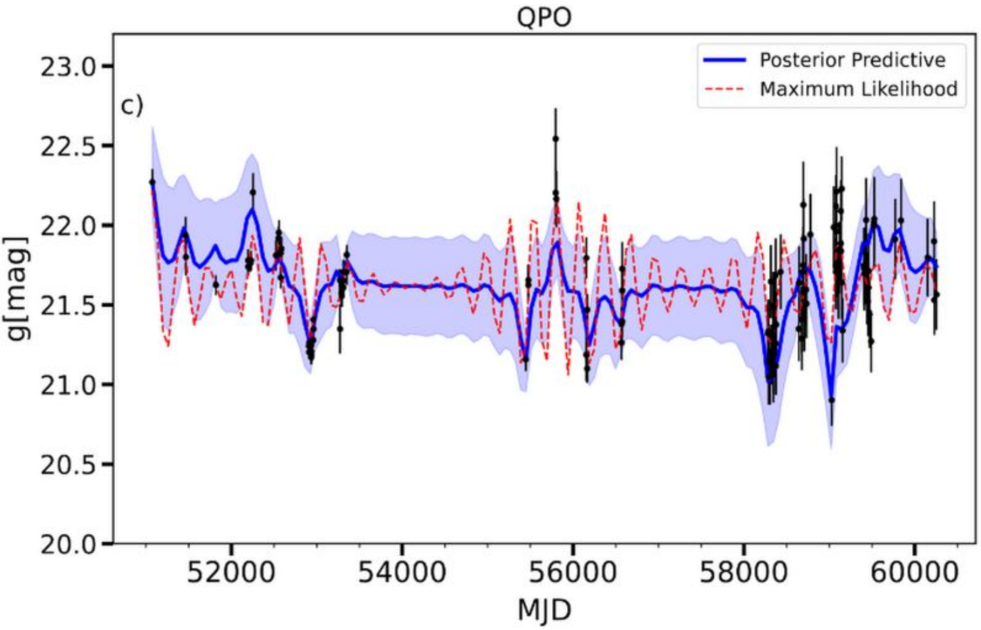
Time Domain: J2320+0024

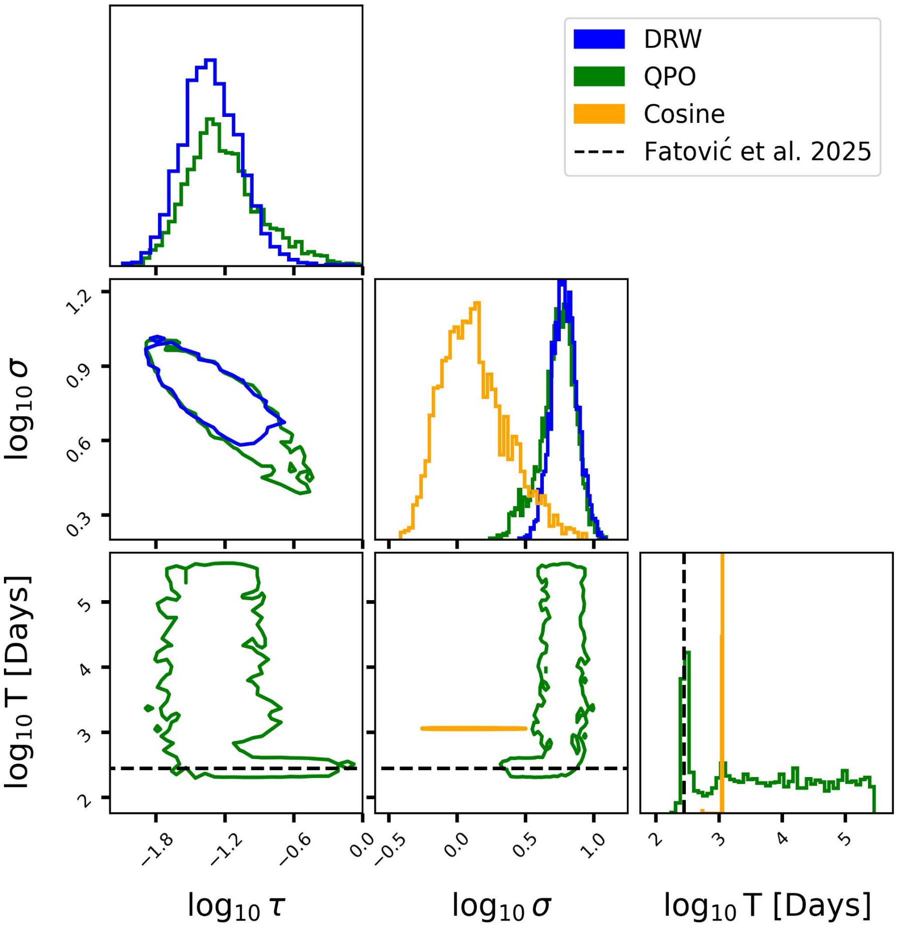


Periodic $$\Sigma_{ij} = \frac{1}{2}\sigma^2 \cos\left(\frac{2\pi|t_i - t_j|}{T}\right)$$



Time Domain: J2320+0024

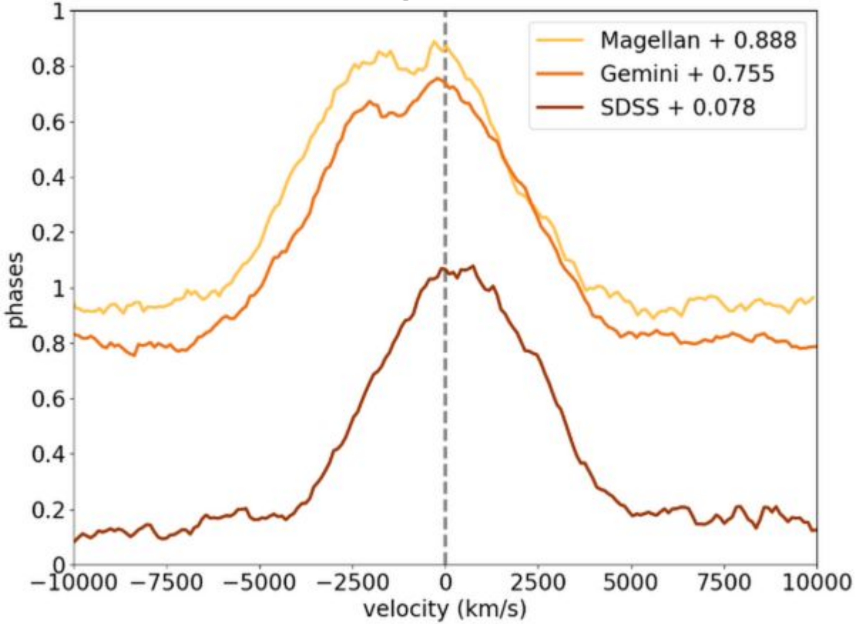




QPO $$\Sigma_{ij} = \frac{1}{2}\sigma^2\tau\exp\left(-\frac{|t_i - t_j|}{\tau}\right)\cos\left(\frac{2\pi|t_i - t_j|}{T}\right)$$

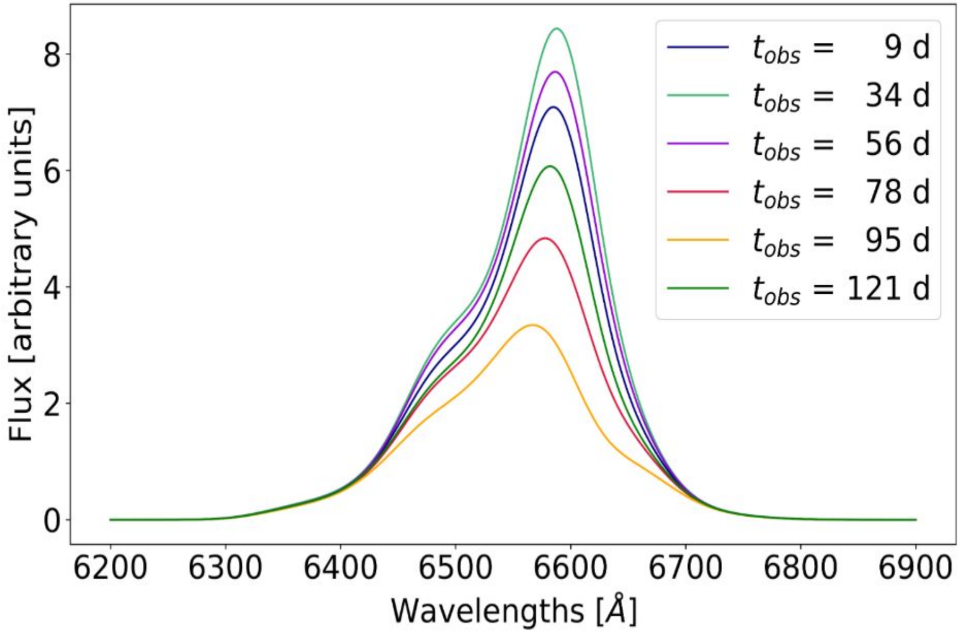
Time Domain: J2320+0024

MgII Line



Fatovic et al. 2025

Model (no fit)



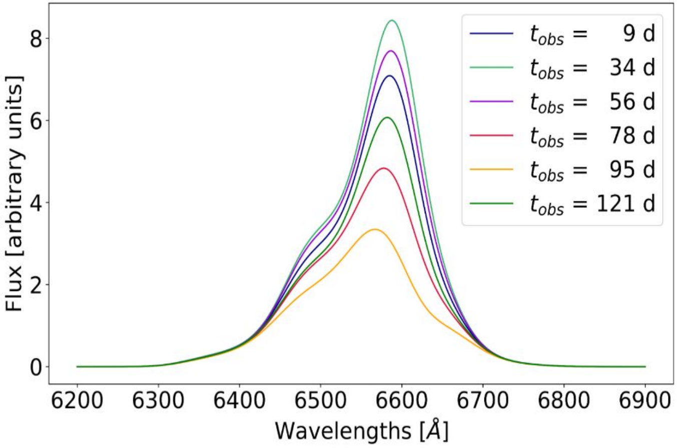
Sottocorno et al. 2025

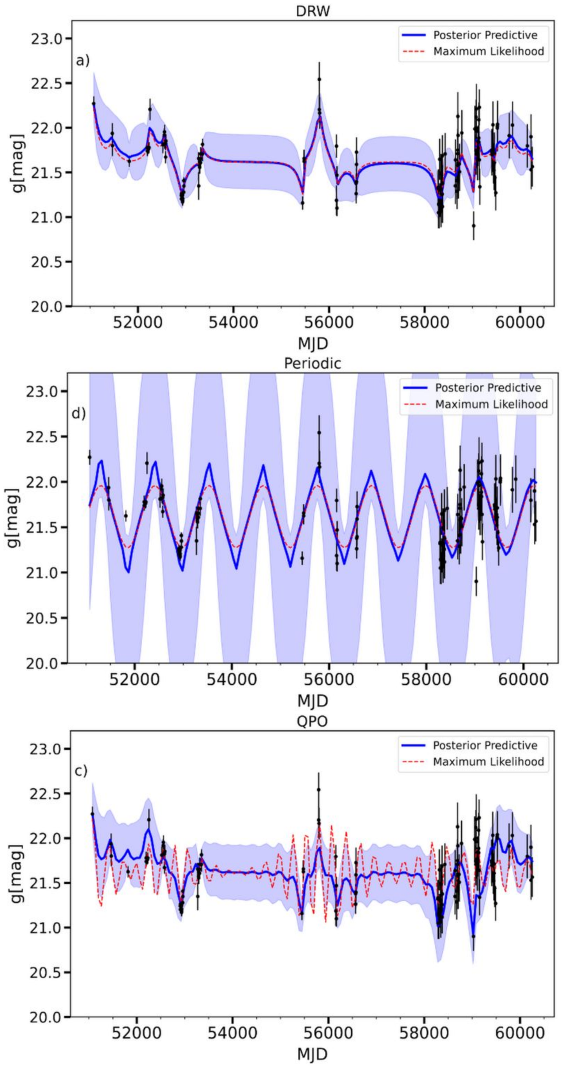
Conclusion n.2

Light curve of J2320+0024:

- **No evidence for periodicity**

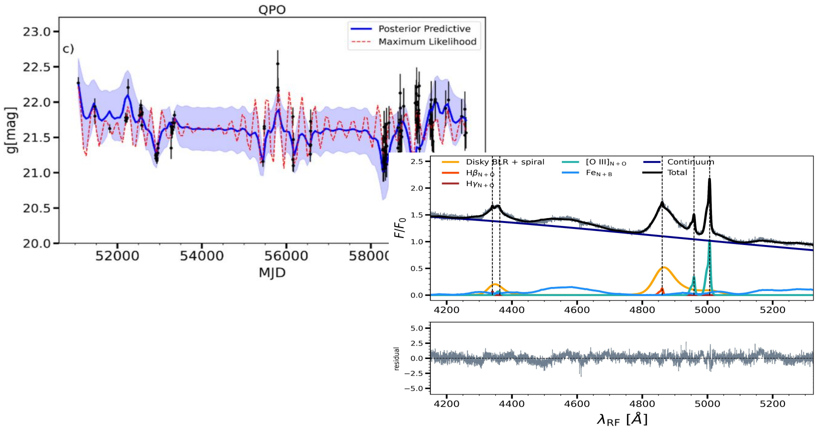
- **Spectral variability** can be explained via disturbed BLR models

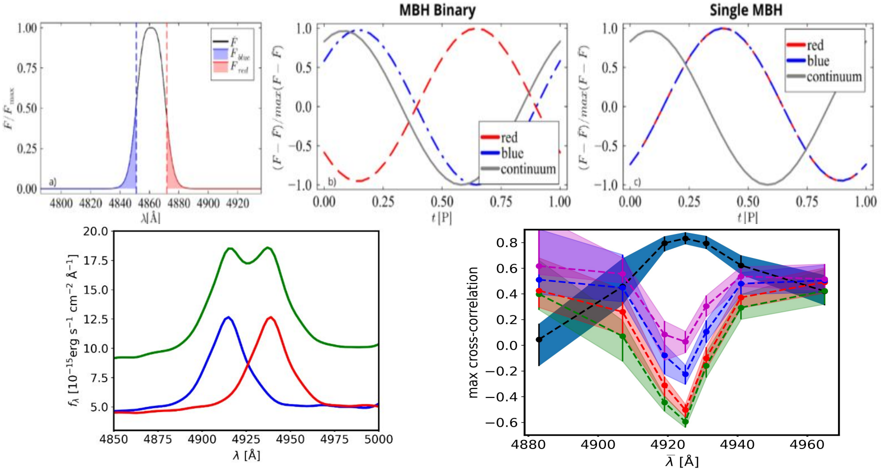




Take home messages,

- **Bayesian analysis** is a powerful tool and could give important insights both on light curves and spectrum





- **Simultaneous analysis** and **full modelling** of light-curve and spectra (RM style) is the key to unveil MBHBs

Take home messages,

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are these useful for IMBHs?

- **Simultaneous analysis** and **full modelling** of light-curve and spectra (RM style) is the key to unveil MBHBs

Take home messages,

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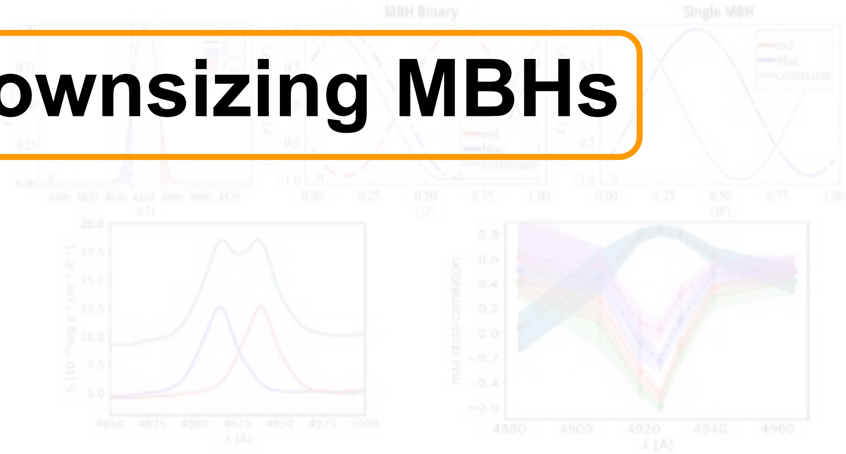
are these useful for IMBHs?



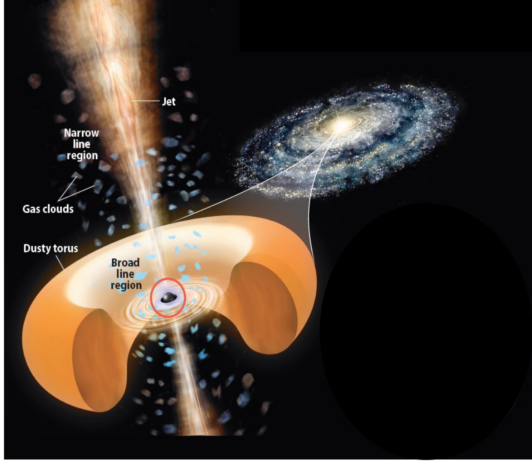
Downsizing MBHs

Upsizing X-ray binaries

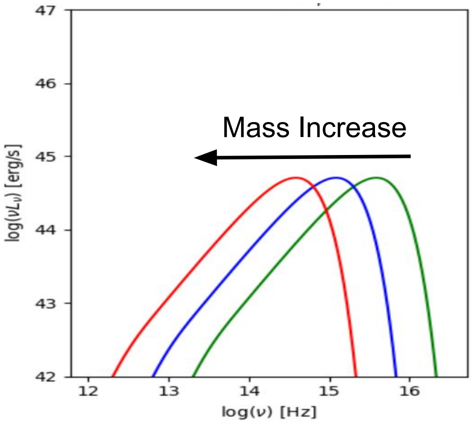
- **Simultaneous analysis and full modelling** of light-curve and spectra (RM style) is the key to unveil MBHBs

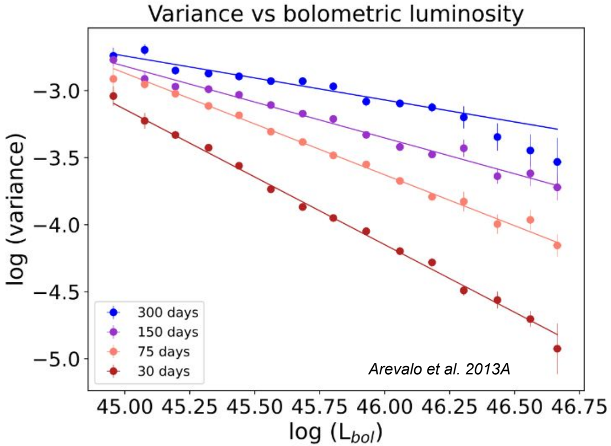
Downsizing MBHs

$$10^6 M_\odot \quad @ \quad 0.1 f_{edd} \quad \begin{cases} R_{B-H\beta} \simeq 3.3\ ld \simeq 0.003\ pc \\ \mathrm{FWHM}_{B-H\beta} \simeq 1223\ \mathrm{km/s} \end{cases}$$



But IMBH are offset… should we expect clear red/blue shift?





Should we expect higher variability? But still in the optical?