Long-term monitoring of super-massive binary candidates: Variability in the broad line and continuum

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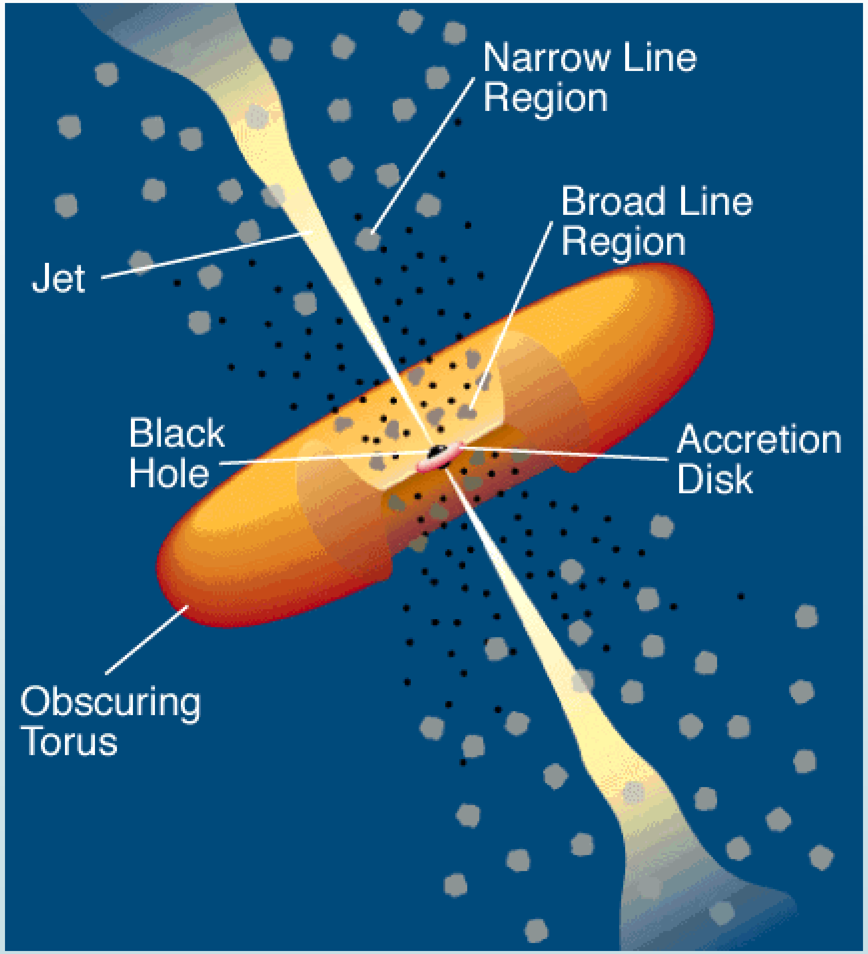
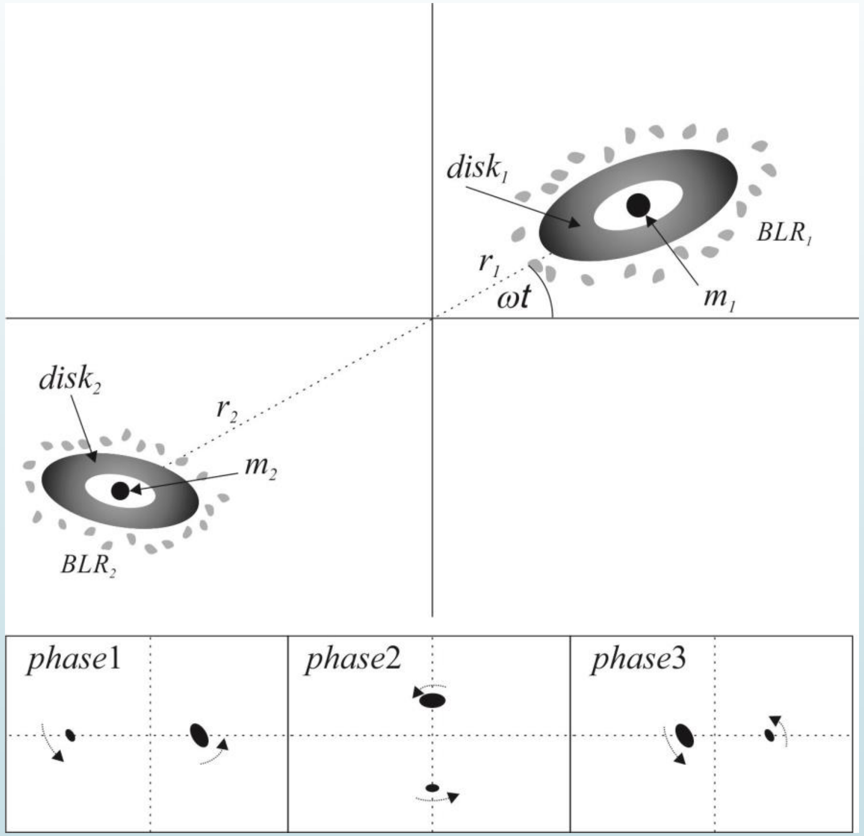
Structure of AGN - reminder

- BH, accretion disk, BLR clouds, NLR clouds, jets, torus.
- BH driving all
- accretion disk generate intense continuum radiation covering IR to Xray.
- heated gas in BLR produce broad spectral lines
- jets generate radiation in radio domain
- torus imprint absorption features in spectra



Model and assumption - accretion disk

- there is a very good reasons for existence of binary system (galaxy mergers, collisions)
- system contains two BHs of similar mass orbiting around common center of mass.
- additional variables are mutual distance *R* and mass ratio *q*
- in general case, both BHs have accretion disks and surrounding broad line regions.
- orbital plane inclination is arbitrary.
- orbital paths are elliptical, so the mutual distance variate during the rotation.
- we distinguish three interesting positions (*phase* 1,2,3) during the rotation.



Intentions

- to establish sustainable model of binary AGN system emission in continuum and discrete spectrum.
- to investigate mechanism of variability during observational time period.
- to investigate main parameters with most significant influence on variation.
- to examine the relative magnitude of variability of AGN binary system emission.

Model and assumption - dynamics

$$|\vec{v}_i| = 1.5 \times 10^3 \sqrt{\frac{0.1[pc]}{R}} \sqrt{\frac{m_1 + m_2}{2 \times 10^8 [M_{sun}]}} \times \left(\frac{2m_1 m_2}{m_i (m_1 + m_2)} \right) \sin(\theta_{orb}) \cos(\omega t)$$

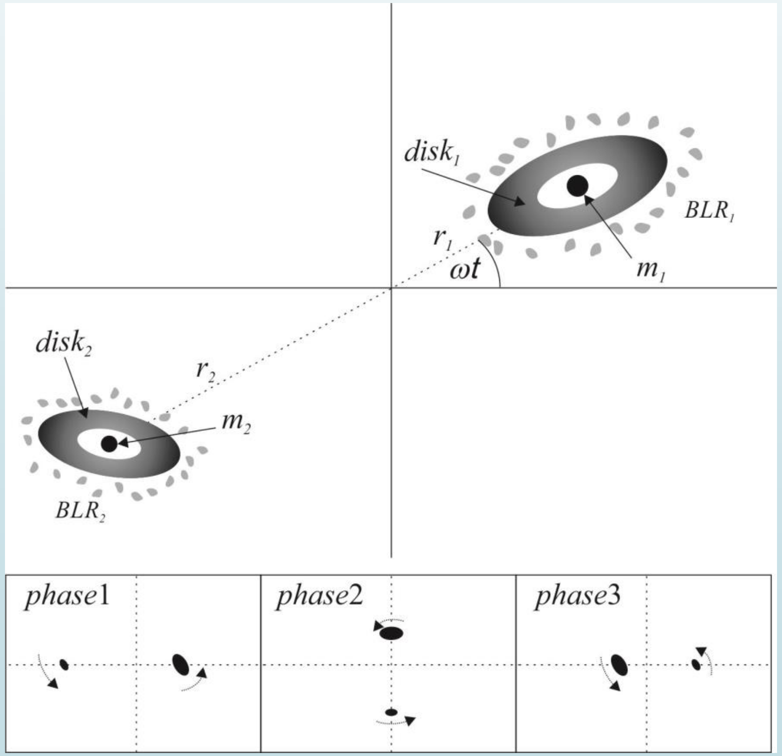
Yu & Lu, 2001
Popović, 2012

$$P_{orb} = 210 \left(\frac{R}{0.1[pc]} \right)^{3/2} \left(\frac{2 \times 10^8 [M_{sun}]}{m_1 + m_2} \right)^{1/2}$$

- v_i – radial velocity of *i*-th component [km/s] and P_{orb} – orbital period [years].
- relative distance from the center of mass is given by:

$$r_1 = \frac{q}{1+q} R \qquad r_2 = \frac{1}{1+q} R \qquad R = r_1 + r_2 \qquad q = \frac{m_1}{m_2}$$

- variation of R depends on the ellipticity of the BHs orbit.



Model and assumption – accretion disk

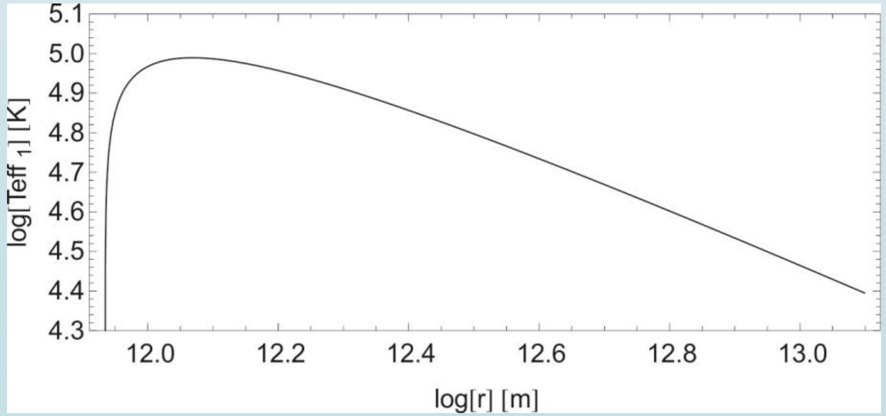
- we assume standard optically thick, geometrically thin disk (Shakura & Sunyaev, 1973).
- disk is confined with inner R_{in} and outer R_{out} diameter.
  $R_{in} = 12Gm_i/c^2$ (Lynden-Bell, 1969).
  $R_{out}=r_o(m_i[M_{sun}]/10^9)^{2/3}$ (r_o~4.5 Vicente, 2014).
- we assume that temperature decline within the disk radius according to the relation:

$$T_{eff}[K] = 2\times 10^5 \left(\frac{0.1}{\epsilon}\right)^{1/4} \left(\frac{f_E}{0.3}\right)^{1/4} \left(\frac{10^8}{mi}\right)^{1/4} \left(\frac{R_{in}}{R}\right)^{\beta} \left(1-\sqrt{\frac{R_{in}}{R}}\right)$$

Yan et al. 2014

$$\beta = 3/4, f_E = \frac{\dot{M}_{acc}}{\dot{M}_E}, \dot{M}_E = \frac{4\pi m_p G m_i}{\epsilon c \sigma_T}$$

temp. profile of unperturbed disk



Model and assumption – accretion disk

- in compact binary systems (R<0.1pc) mutual disk interaction can perturb temperature profile.
- we expect that this will result in changing the accretion rate, which is expressed with factor $f_E = \frac{\dot{M}_{acc}}{\dot{M}_E}$
- we derive amount of disk perturbation by assuming proportionality $T_{eff}^4 \sim \Omega^2$, (Tanaka, T. 2012)

$$\dot{M} \sim \frac{T^8}{P^{5/2}\rho^{1/2}}$$

- resulting in

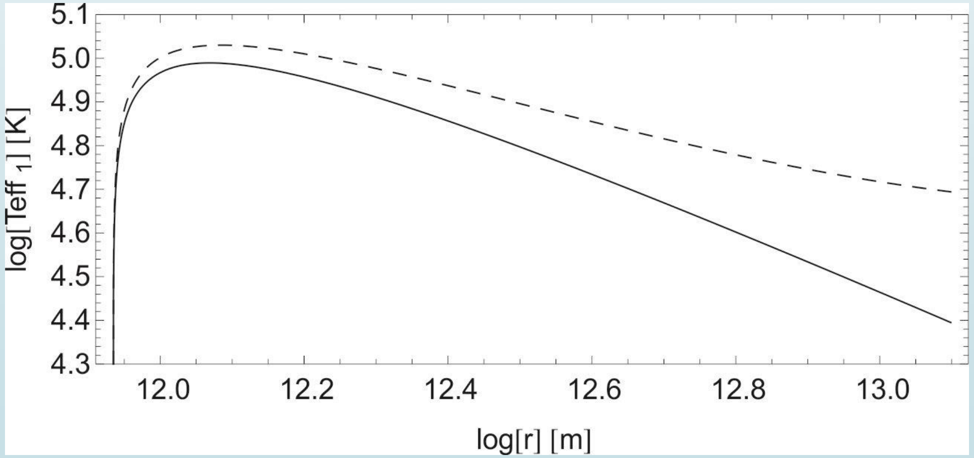
$$f_E^i = f_E^0 \left(1 + \frac{m_j}{m_i}\frac{R}{r}\right)^2$$

$$T_{eff}[K] = T_{eff}^{nonpert} \left(1 + \frac{m_j}{m_i}\frac{R}{r}\right)^{1/2}$$

- R, r – dist. from disk part to the BH centers

temp. profile of perturbed disk - dashed line

image show very compact case



- for more compact system, perturbation of temp. profile is higher

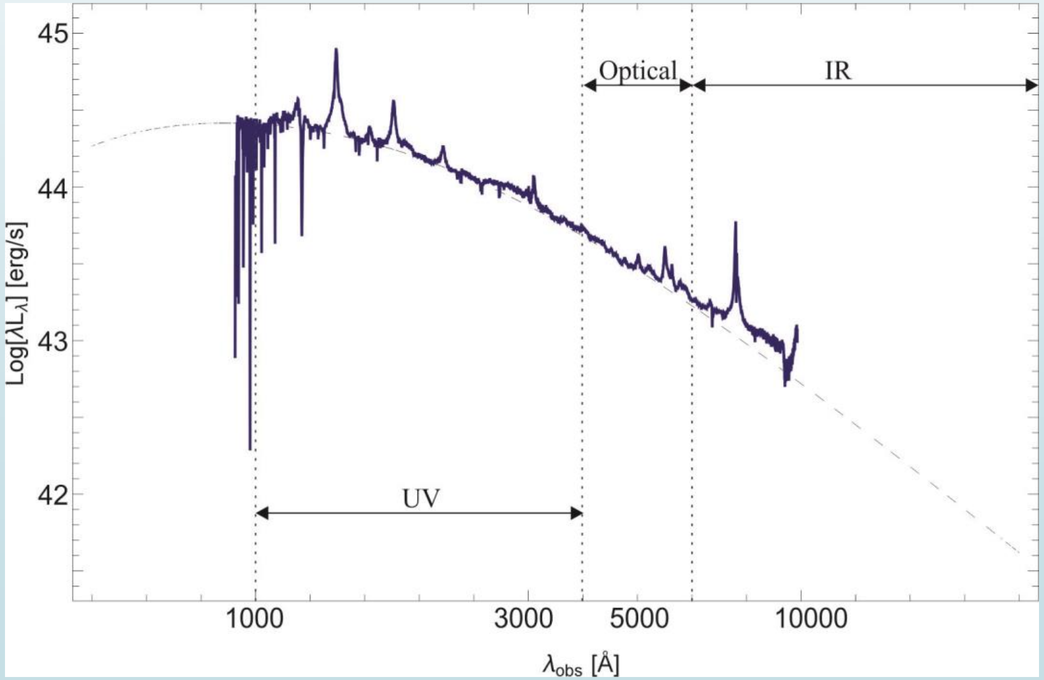
Model and assumption – emission

- emission mechanism is based on the thermal radiation
- in the inner parts of the disk synchrotron and inverse Compton radiation is significant.
- we compute total luminosity using black body distribution.

$$dL = \frac{2hc^2}{\lambda^5} \frac{dS\cos(\theta)}{\left[exp\left(\frac{hc}{\lambda k_B T_{eff}}\right) - 1\right]}$$

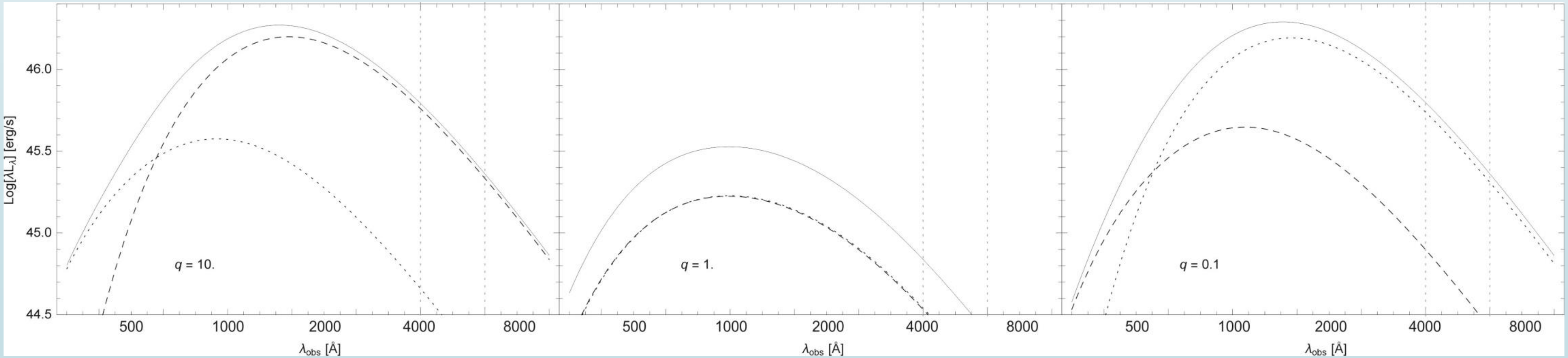
$$L(\lambda) \propto \int_{S_{disk}} \lambda dL(\lambda, T_{eff})$$

- model applied in case of 3C273



Model and assumption – binary system emission

- Spectral energy distribution for binary system of two black holes, where dashed and dotted lines presents SED for BH components of mass m_1 and m_2, respectively, and full line presents cumulative SED for both components in the system. Vertical lines confine UV, optical and IR energy bands. Three images represent cases of different mass ratio, q = 10, q = 1 and q = 0.1.
- small mass – hard SED, big mass – soft SED.



Model and assumption - BLR

- in close environment of a disk there are gas region heated by disk emission.
- due to the recombination it produce broad emission lines, therefore called Broad Line Region (BLR).
- For binary systems we discuss two distinctive cases:
  - when both components have it's respectful BLR and
  - when two BHs are surrounded with one common BLR.
- BLR size is estimated within empirical relation (Kaspi et al., 2005):

$$\frac{R_{BLR}}{10\ ld} = (2.21 \pm 0.21) \times \left[\frac{\lambda L_\lambda\ (5100\text{Å})}{10^{44} erg\ s^{-1}}\right]^{0.69 \pm 0.05}$$

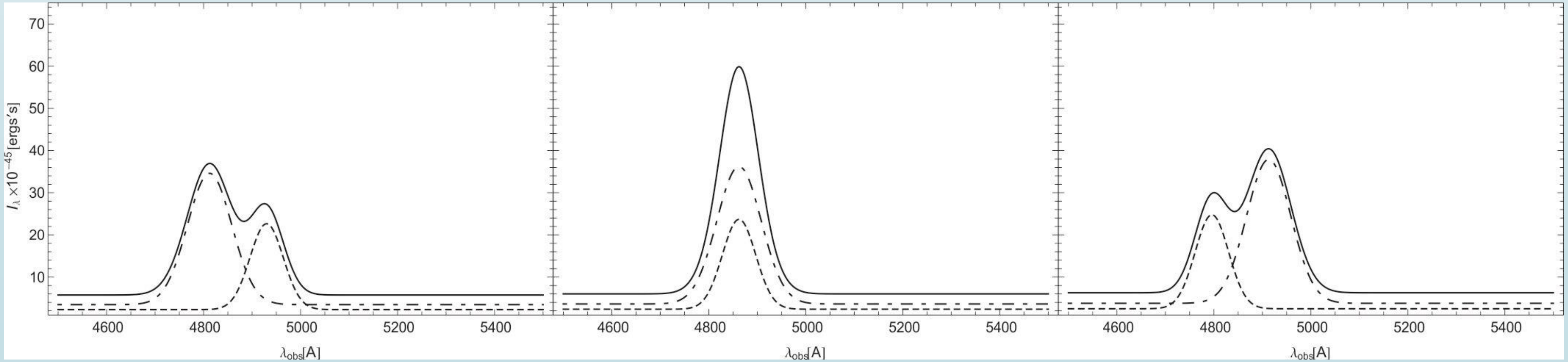
- λL_λ(5100A) – total disk luminosity at λ = 5100A.
- To estimate line intensity $I_{\lambda o}^{H\beta} = \lambda L(H_\beta)$, we use (Wu et al. 2004):

$$log R_{BLR}[ld] = 1.381 + 0.684 \times log\left(\frac{\lambda L(H_\beta)}{10^{42} erg\ s^{-1}}\right)$$

Model and assumption - BLR

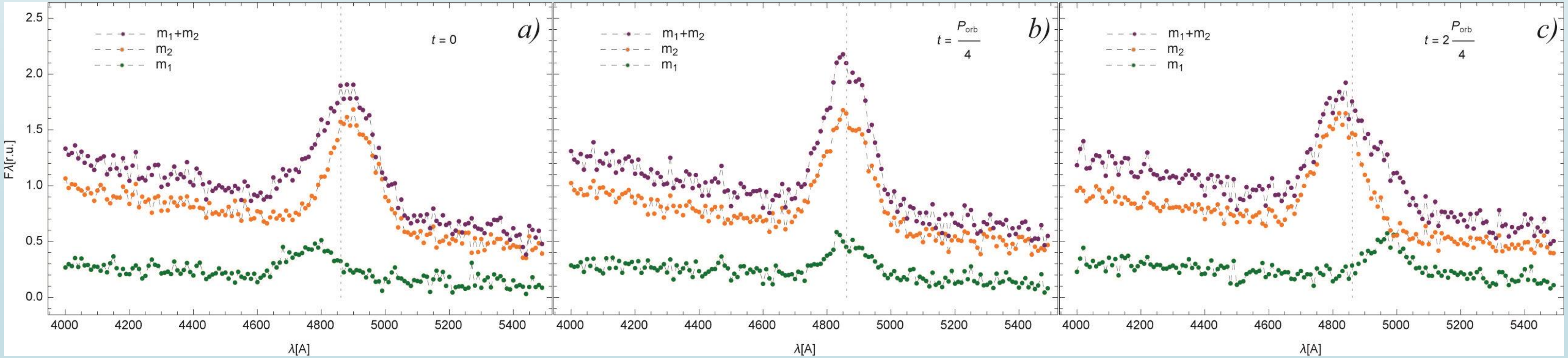
- based on the virial theorem we estimate velocity distribution and line width σ_i
- line shift due to the radial velocity >> gravitational line shift.
- total line profile is $I_{tot}(\lambda)=I_1(\lambda)+I_2(\lambda)$ where:

$$I_i(\lambda) = I_i(\lambda o) \times exp\left[-\left(\frac{\lambda - \lambda o(1 + z^i_{dopp})}{\sqrt{2}\sigma_i}\right)^2\right]\cos(\theta)$$



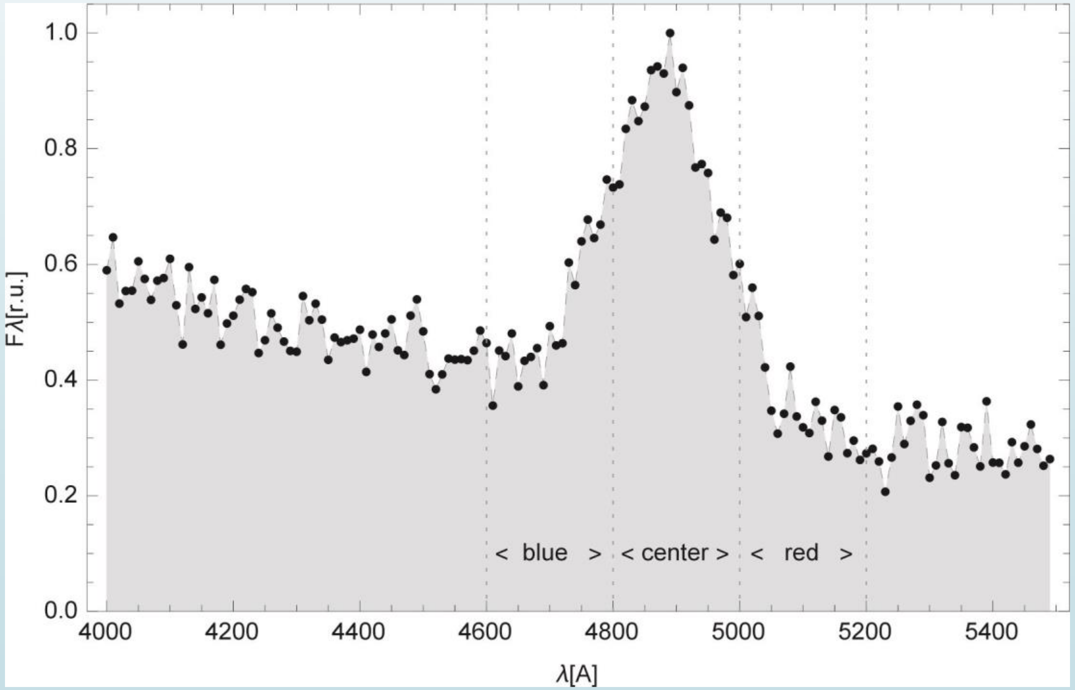
Simulations and results – combined spectra

- in computation we include white noise.
- Fig below shows Hβ line and continuum emission with white noise included, in three separate positions during the complete rotation of BBH system.
- Some of used parameters has values: $m_1=3x10^8M_{sun}$, $m_2=8x10^8M_{sun}$, R=0.05pc, e=0.3.
- we here observe combined Hβ line (violet dots)
- smaller BH mass – larger shifts and vice versa.
- superposition of lines induce asymmetric deviation of resultant line.
- common Hβ line variate in it's intensity and width.



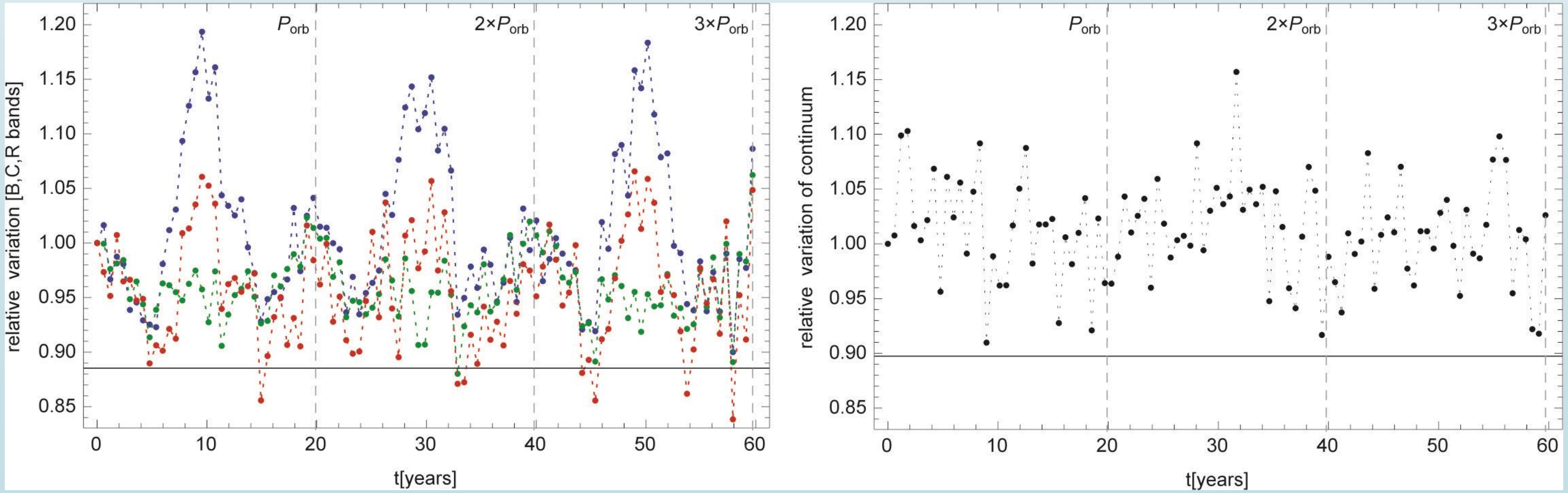
Simulations and results – Hβ sectors

- in order to study variability of Hβ line we divide it into a three sectors blue (4600-4800A), center (4800-5000A) and red (5000-5200A).



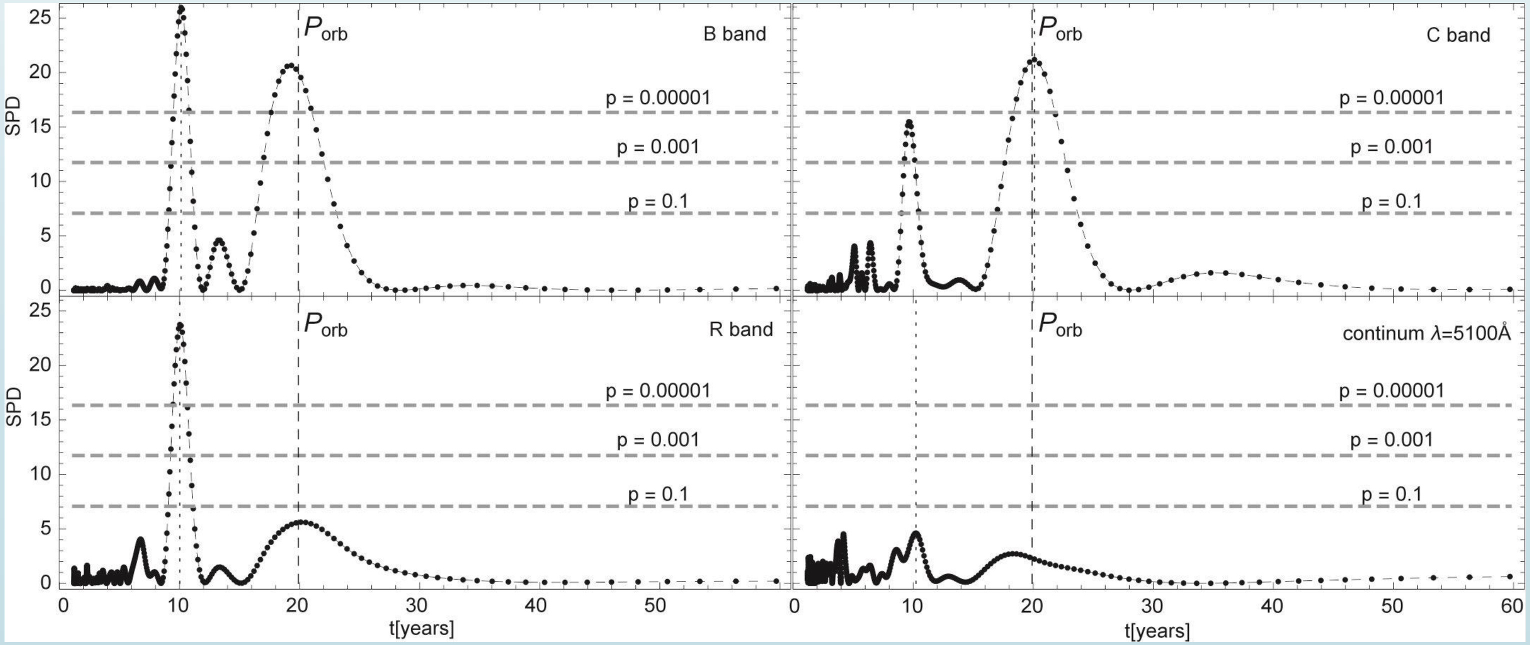
Simulations and results - variability

- Relative variation of B,C,R sectors (left panel) and continuum at λ = 5100Å (right panel) during three full orbit of considered binary black hole system.
- Highest variation is shown in the line wings (blue and red domain), and significantly lower in the central part of the line. Such behavior has mostly Dopplerian character and consequently produce highest variability when Hβ lines of two orbiting components are at highest separation.
- On the other hand, continuum variability is smaller in amplitude, induced mostly by applied white noise, and consequently very hard to find expected periodicity. In this case superposition of continuum emission of two BHs is such that cover each other, so the overall effect decrease continuum variations.



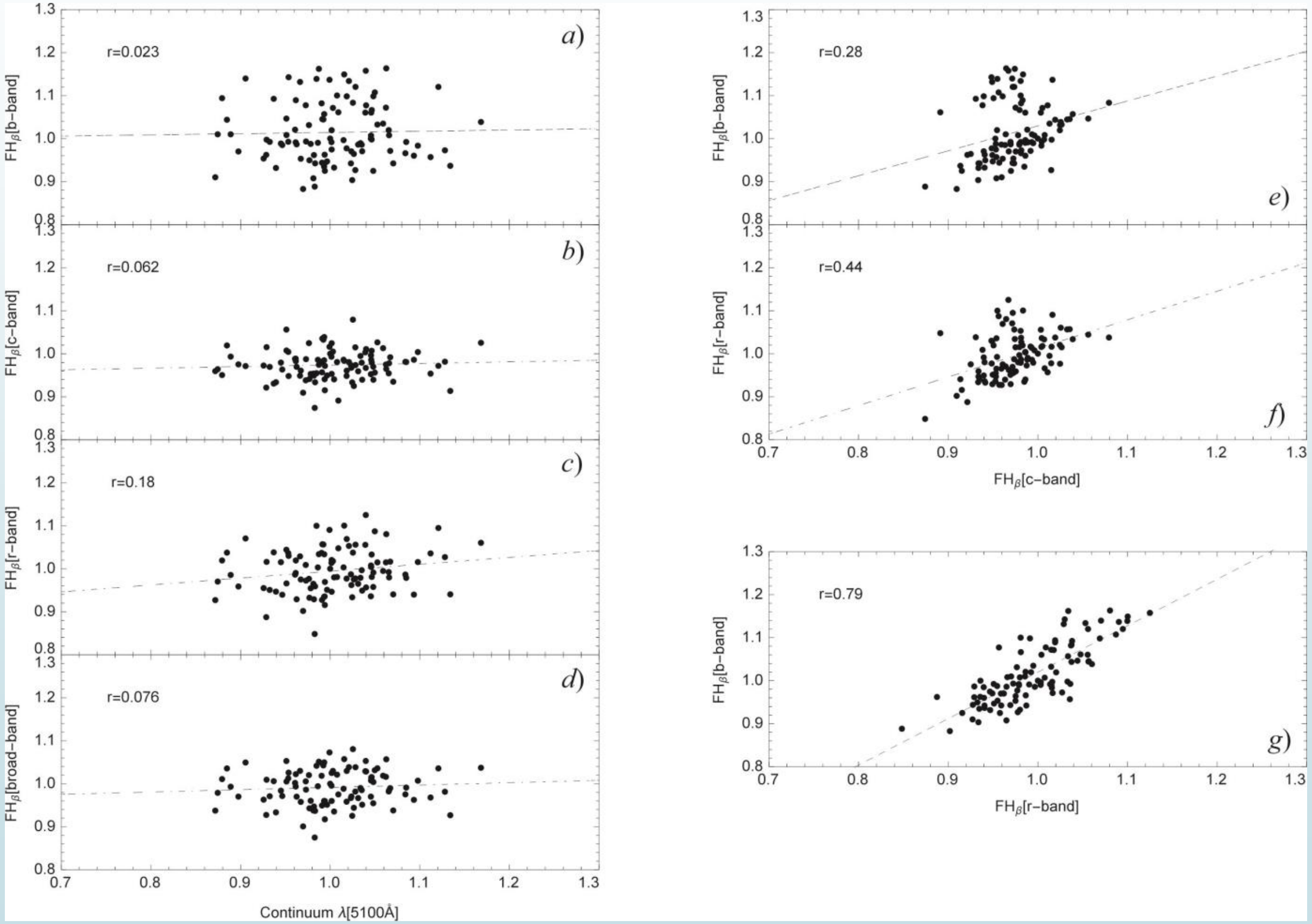
Simulations and results - periodograms

- we try to extract some useful data form computed variability.
- Lomb-Scargle periodograms for B, C, R bands and continuum at λ = 5100Å.
- horizontal significance level lines for three different values of parameter p (False Discovery Rate), p = 0.1, p = 0.001 and p = 0.00001. SPD (Spectral Power Density). p = 0.1 it means that there is a 10% probability of mistake
- B,C,R shows distinctive peaks.
- Nature of variability is such that shows periodic maximums on 10 and 20 years.
- continuum has small peaks with very low confidence.



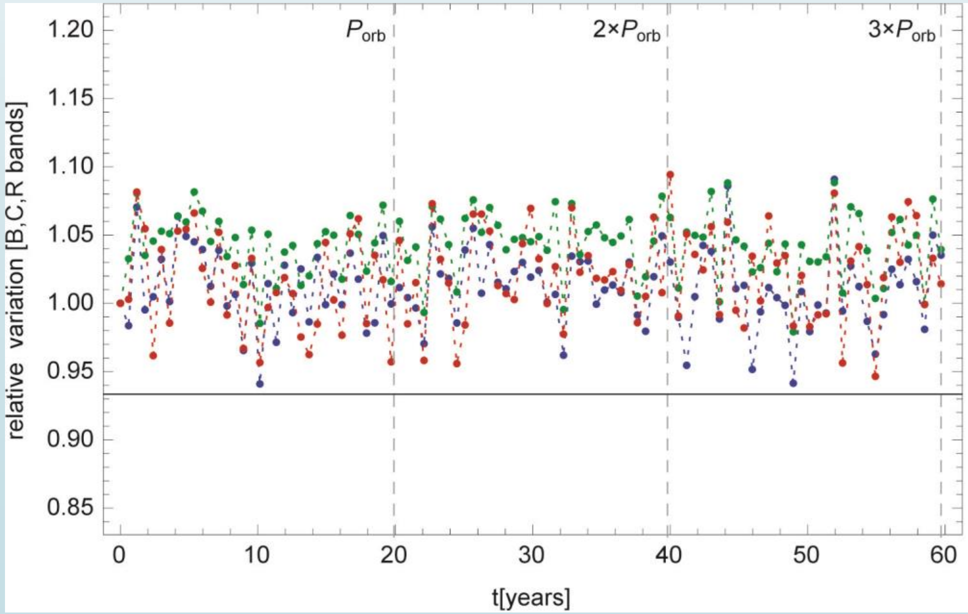
Simulations and results - correlations

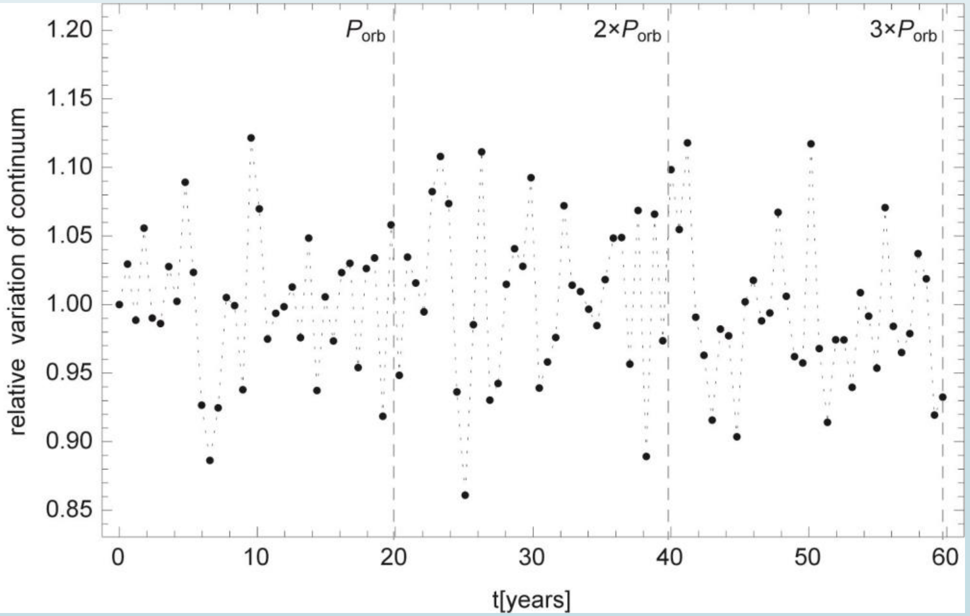
- correlations of B,C,R sectors in Hβ line and continuum are very low.
- correlation between Hβ sectors are significant.
- this behavior shows true doppler nature of variability.



Simulations and results – common BLR

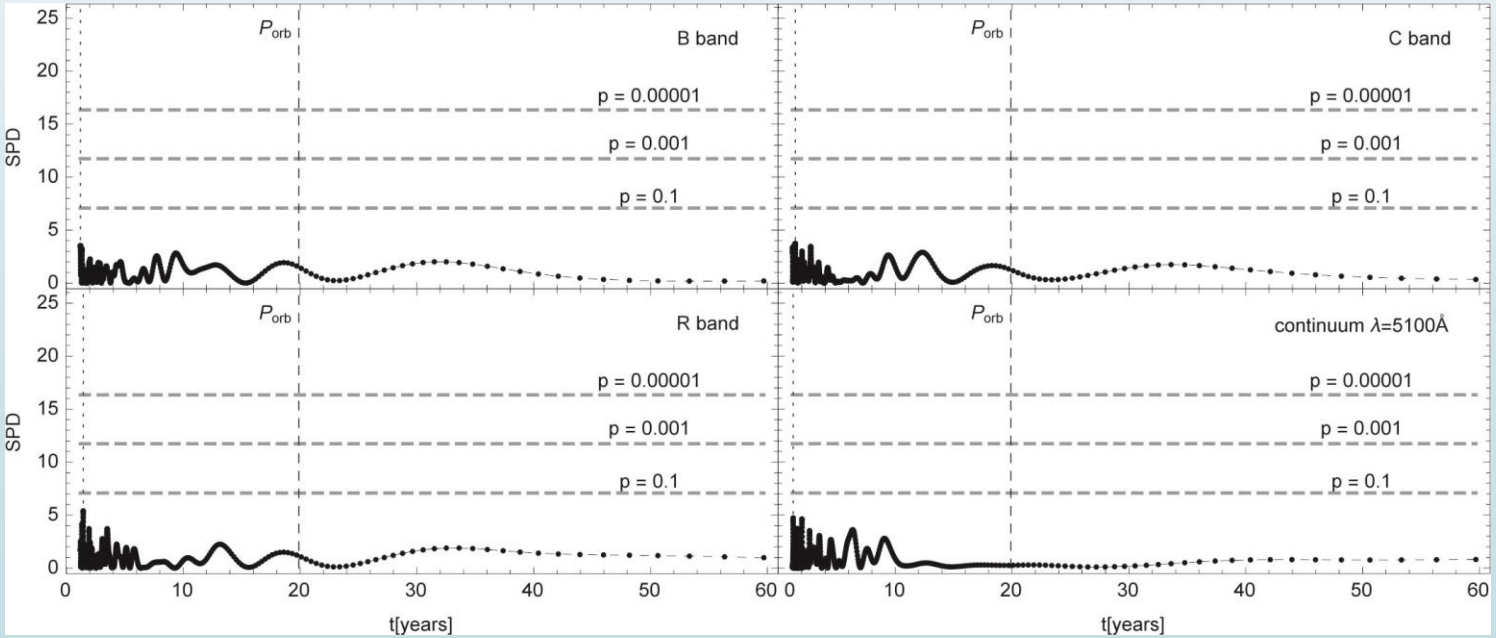
- Case of common BLR
  - induced variations in Hβ line are overlapped by white noise. They have low intensity.
  - variation in continuum hasn't periodic nature





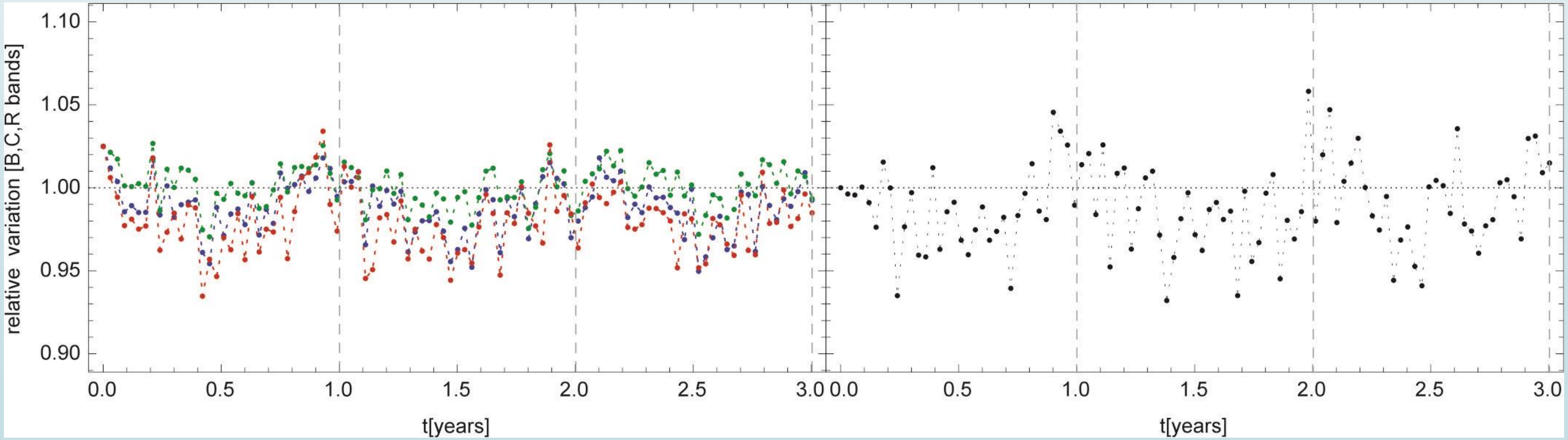
Simulations and results - periodograms

- Case of common BLR
  - induced variations in Hβ line are overlapped by white noise. They have low intensity.
  - variation in continuum hasn't periodic nature
  - no periodicity could be found



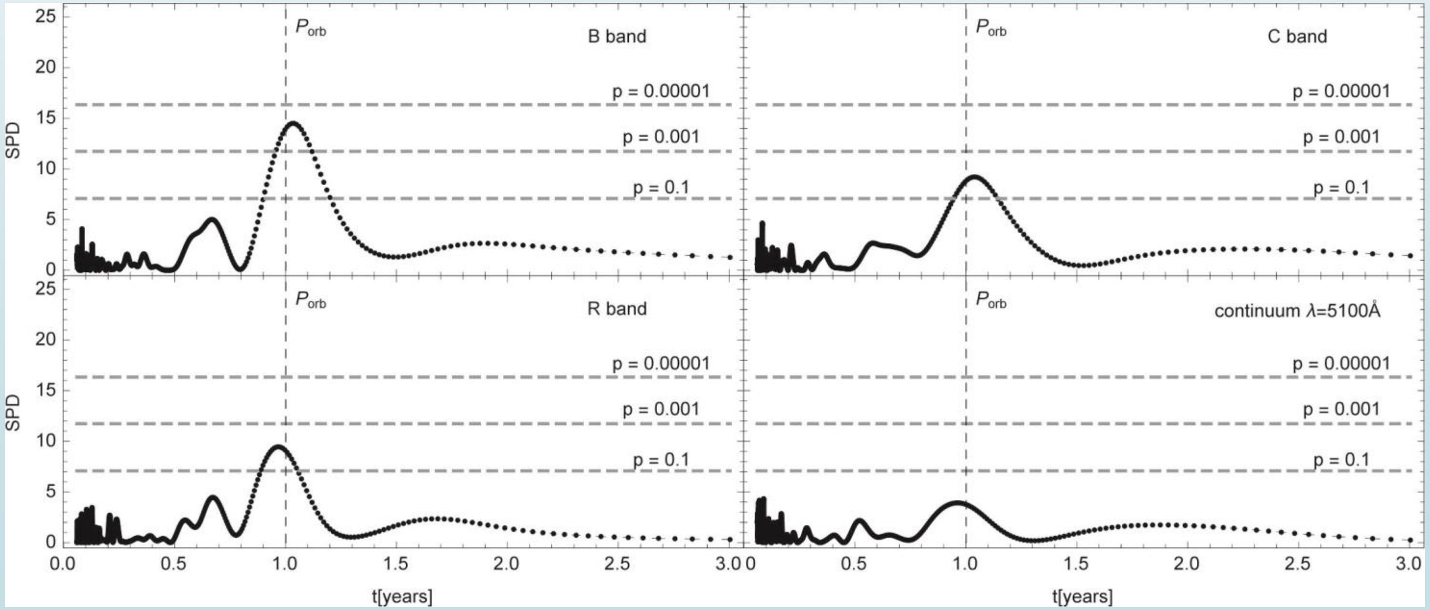
Simulations and results – very compact systems

- Case of very compact systems
  - mutual distance is R=0.01pc, eccentricity high e=0.6, $m_1=3x10^8M_{sun}$, $m_2=8x10^8M_{sun}$.
  - small variation in common BLR could be recorded.
  - periodograms show low significance peaks.



Simulations and results - periodograms

- Case of very compact systems
  - mutual distance is R=0.01pc, eccentricity high e=0.6, $m_1=3x10^8M_{sun}$, $m_2=8x10^8M_{sun}$.
  - small variation in common BLR could be recorded.
  - periodograms of Hβ line variations show low significance peaks.



Conclusions

- presented simple model can reproduce the SED and Hβ line spectrum of binary AGN.
- variability has mostly Dopplerian character.
- variability is clearly defined mainly in Hβ line.
- parameters with most influence are BH masses, mutual distance, eccentricity of the orbits.
- variability in compact cases with single BLR is induced by mutual interaction.

References:

- Yu, Q., & Lu, Y., 2001, A&A, 377, 17
- Popović, L. Č. 2012, NewAR, 56, 74
- Lynden-Bell, D., 1969, Nature, 223, 690
- Vicente, J. J., Mediavilla, E., Kochanek, C. S., Munoz, J. A., Motta, V., Falco, E, & Mosquera, A. M., 2014, ApJ, 783, 47
- Shakura, N.I., & Sunyaev, R. A., 1973, A&A, 24, 337
- Yan, C. S., Lu, Y., Yu, Q., Mao, S., Wambsganss, J., 2014, ApJ, 784, 2
- Kaspi, S., Brandt, W. N., Maoz, D., Netzer, H., Schneider, D. P., Shemmer, O. 2007, ApJ, 659, 997.
- Wu, X. B., Wang, R., Kong, M. Z., Liu, F. K. & Han, J. L., 2004, A&A, 424, 793
- Tanaka, T. 2012, in 'Tidal Disruption Events and AGN Outbursts', Madrid, Spain, (Edited by R. Saxton and S. Komossa), EPJ Web of Conferences, Volume 39, id.06008

Thank you for attention