Variability of super massive black hole binaries

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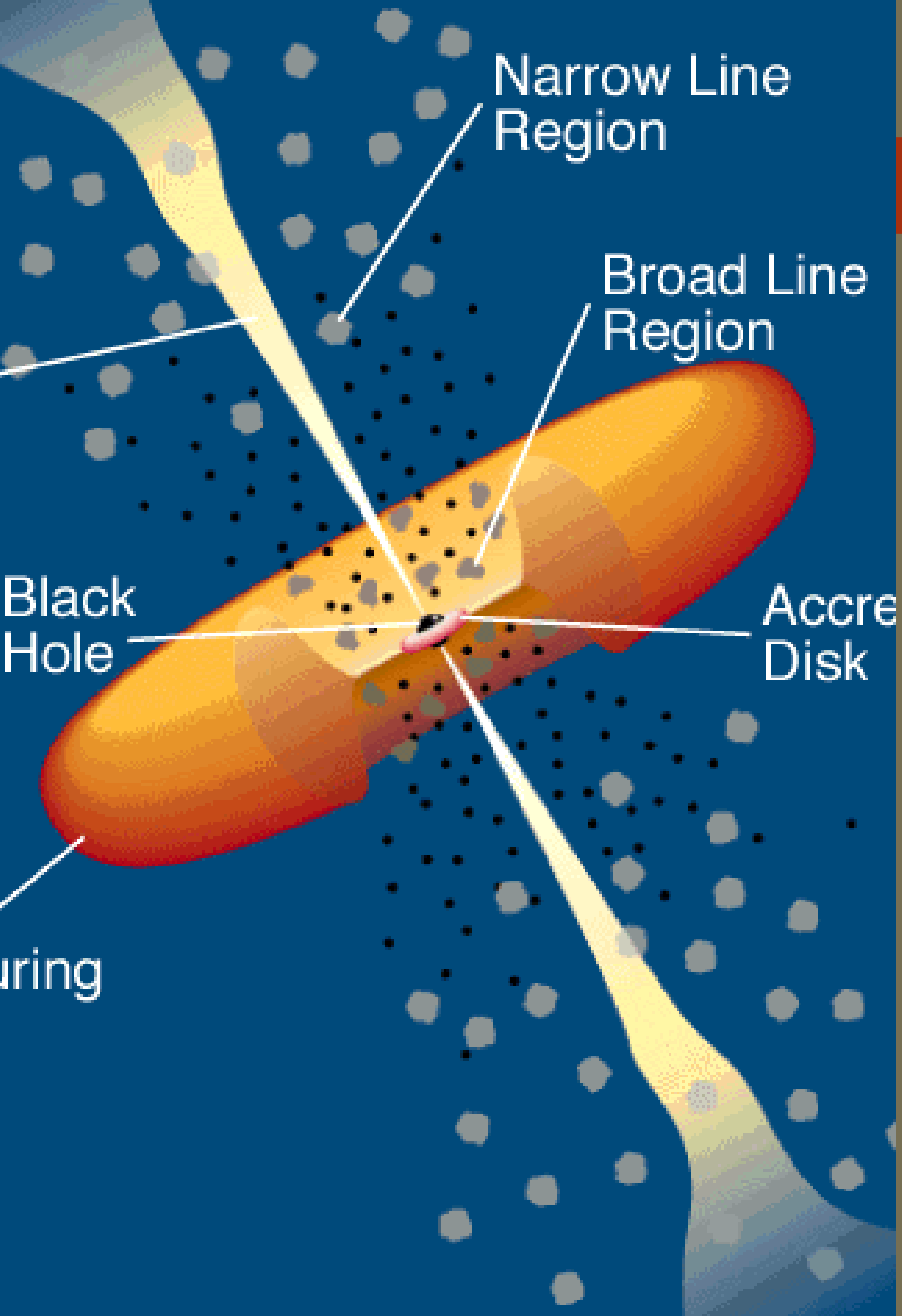
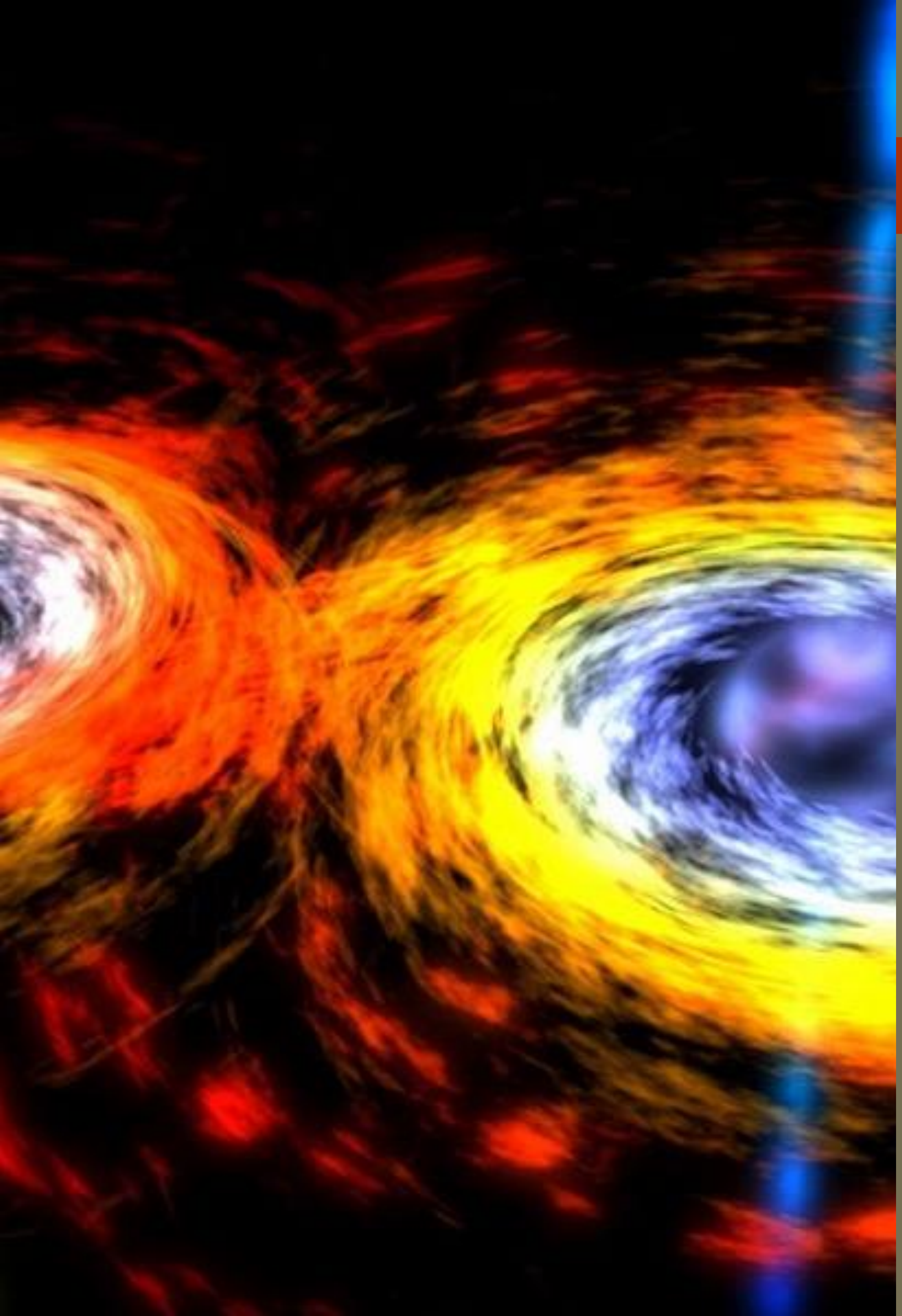


AGN structure - reminder

- 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

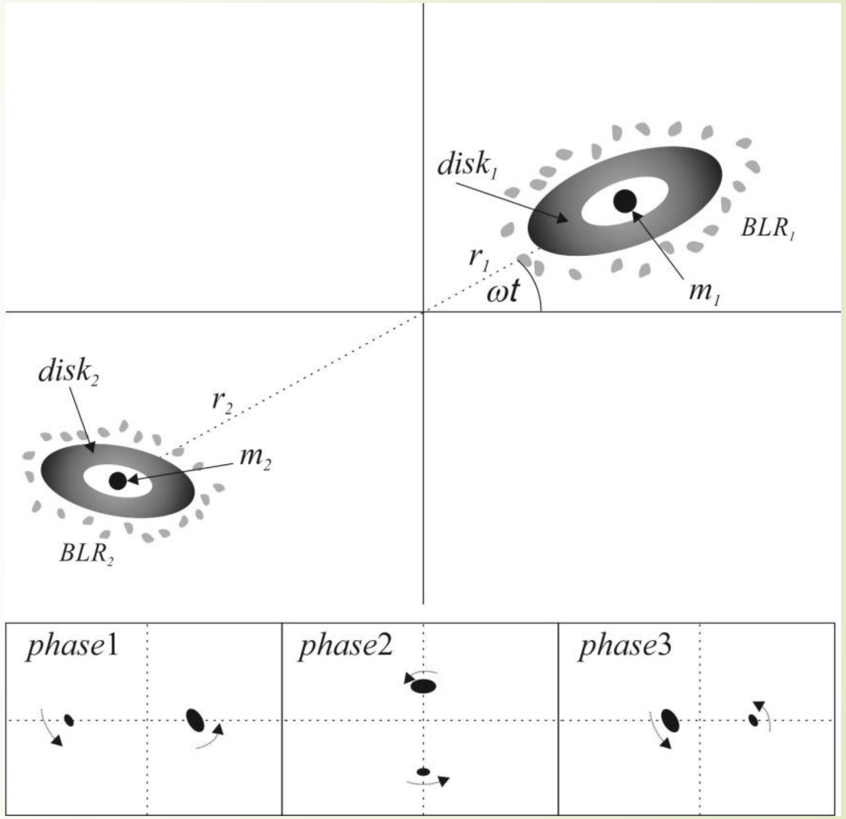


AGN structure – binary system

- AGNs sometimes contains system of two BHs rotating around common center of mass.
- There is a very good reasons for existence of binary system (galaxy mergers, collisions)
- With time system lose energy and eventually collapse (merge).
- Binary systems initially with kpc separation will eventually transform in subparsec phase before merging occur.

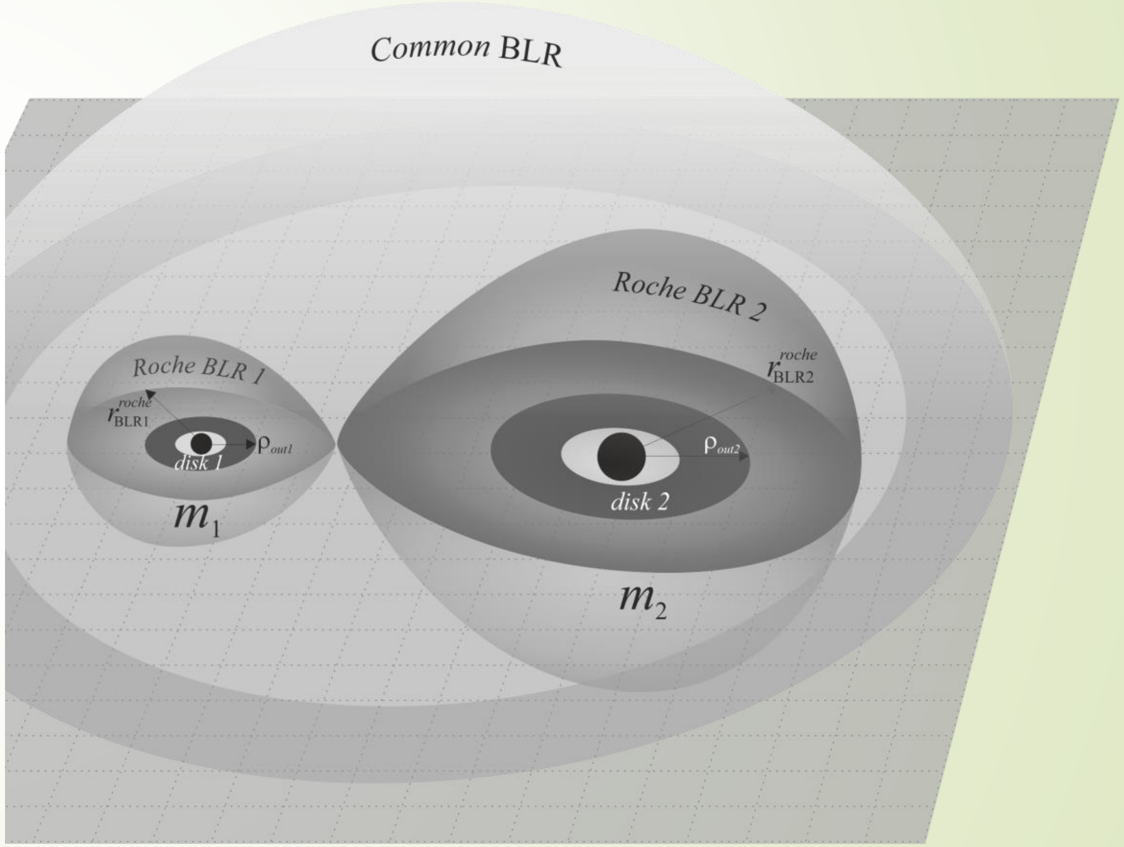
AGN structure – binary system in kpc separation

- system contains two BHs of mass m_1 and m_2, orbiting around common center of mass.
- We parametrize dynamic of the system with
  - mutual distance *R*
  - BH masses (m_1 and m_2) and mass ratio *q*
  - orbital plane inclination (in computation $\theta = 45^{\circ}$).
  - orbital phase ωt.
  - orbital eccentricity *e*.
- in general case, both BHs have accretion disks and surrounding broad line regions.
- orbital paths are elliptical, so the mutual distance variate during the rotation. This could induce variability.
- we distinguish three interesting positions (*phase* 1,2,3) during the rotation.



AGN structure – binary system in subparsec separation

- In case of compact binary systems, there should be a restriction in size of BLR.
- We propose that BLR gas is distributed in space defined by Roche lobes of particular components. It rotate together with BHs and possibly could cause variability.
- Common BLR surrounds entire system and it is illuminated by both disk components.
- Distribution of BLRs emission is unknown and we tested different cases.



Model and assumptions - dynamics

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

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:

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

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

Model and assumptions – accretion disk

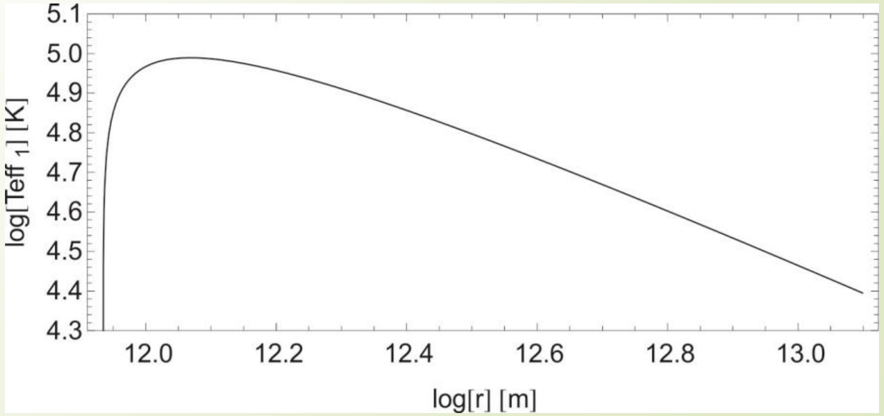
- we assume standard optically thick, geometrically thin disk (Shakura & Sunyaev, 1973).
- disk is confined with inner R_{in} and outer R_{out} diameter.
  $R_{in} = 12Gm_i/c^2$ (Lynden-Bell, 1969).
  $R_{out}=r_o(m_i[M_{sun}]/10^9)^{2/3}$ (r_o~4.5 Vicente, 2014).
- disk dimensions directly depends on the BH mass.
- 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



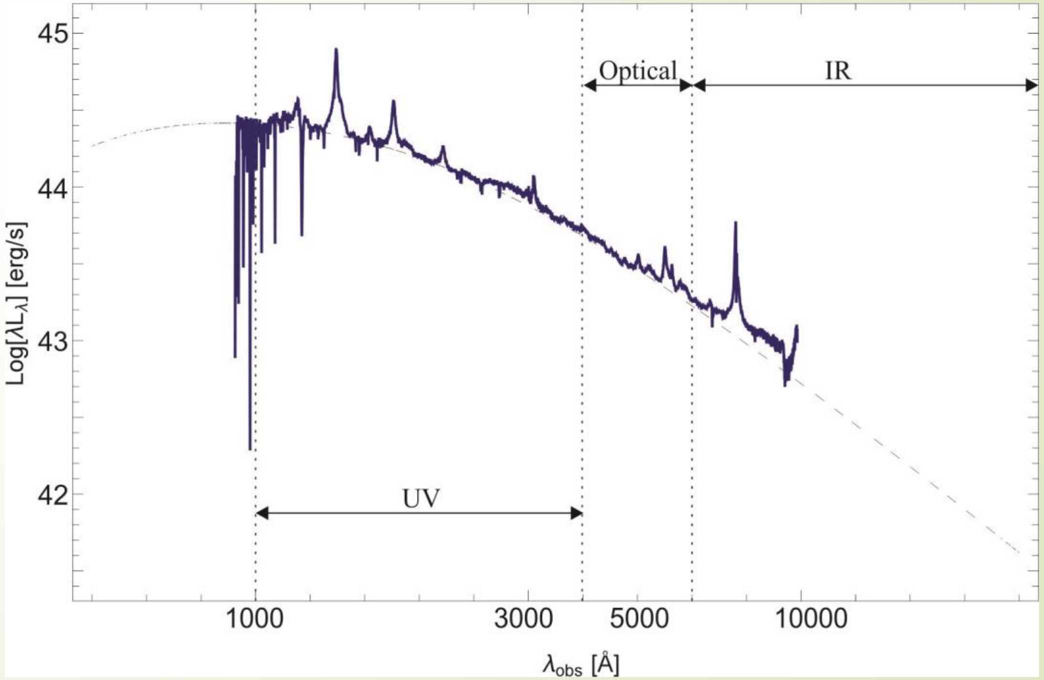
Model and assumptions – single BH emission

- 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 assumptions – accretion disk binary system

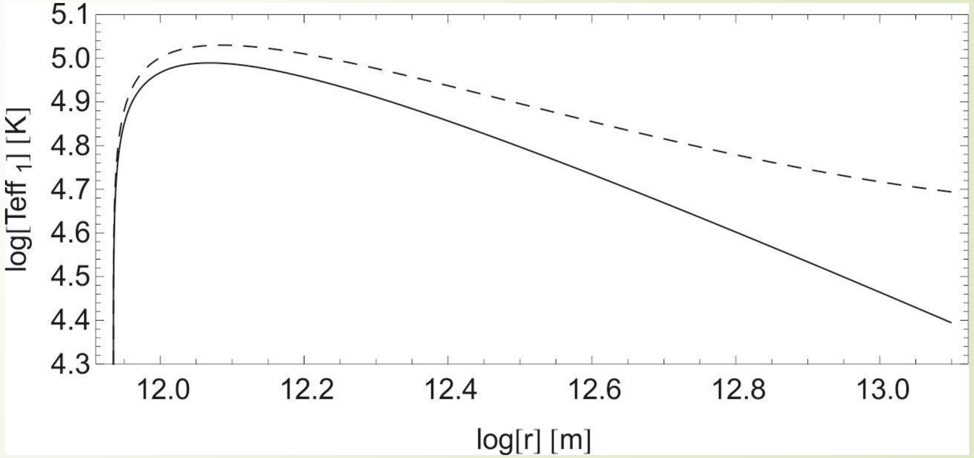
- in compact binary systems (R<0.1pc) mutual disk interaction can perturb temperature profile.
- we derive amount of disk perturbation by using virial theory.

$$T_{eff}[K] = T_{eff}^{nonpert}\left(1 + \frac{m_j}{m_i}\frac{R}{r}\right)^{1/4}$$

- *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
- This is very important since separation could variate due to eccentric orbit

Model and assumptions – relativistic boosting

- Radial velocities of components could be high in compact binaries, so we take in account relativistic boosting effect.
- It is based on the special relativity invariance of photon phase-space density F_ν/ν^3, therefore the apparent flux F_ν at a fixed observed frequency ν is modified from the flux of a stationary source F^0_ν to

$$F_\nu = D^3 F^o_{D^{-1}\nu} = D^{3-\alpha} F^o_\nu$$

D'Orazio, et al., 2015, Nature.

$$D = \frac{1}{\Gamma(1-\beta_{\|})}$$

$$\Gamma = \frac{1}{\sqrt{1-\beta^2}}$$

- We apply this effect on continuum as well as on line spectra.

Model and assumptions - BLR

- standard model propose that in close environment of a disk there are gas regions heated by disk emission.
- It's size directly depend on the disk luminosity.
- BLR size is estimated within empirical relation (Kaspi et al., 2005):

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

- the bigger the BH is, more emission disk produce and consequently BLR is greater.
- To estimate line intensity $I_{\lambda o}^{H\beta} = \lambda L(H_\beta)$, we use (Wu et al. 2004) empirical relation connecting BLR size and line flux:

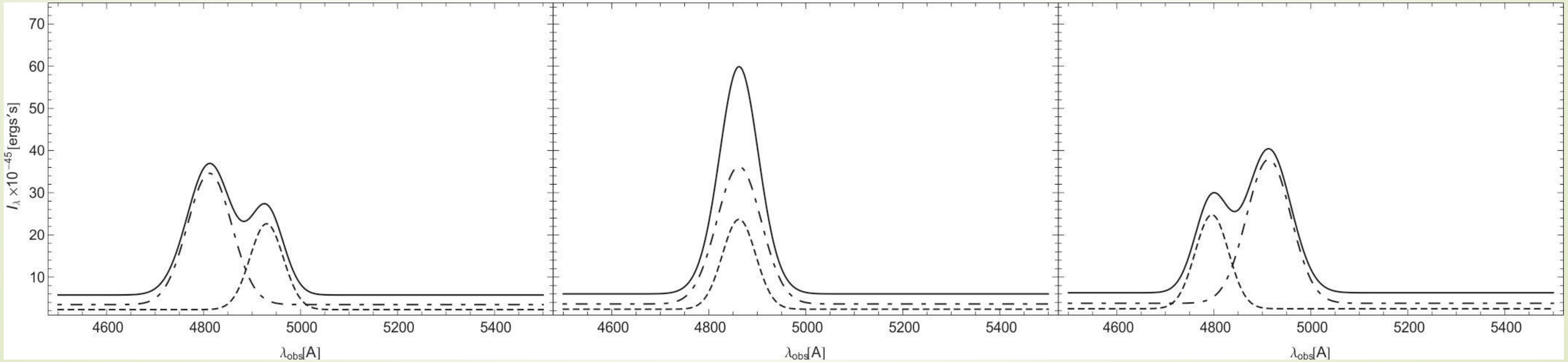
$$log R_{BLR}[ld] = 1.381 + 0.684 \times log\left(\frac{\lambda L(H_\beta)}{10^{42} erg\ s^{-1}}\right)$$

Model and assumptions – line width – kpc separation

- Velocity distribution is high, so line produced are very broad.
- based on the virial theorem we estimate velocity distribution in BLR which give us 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:

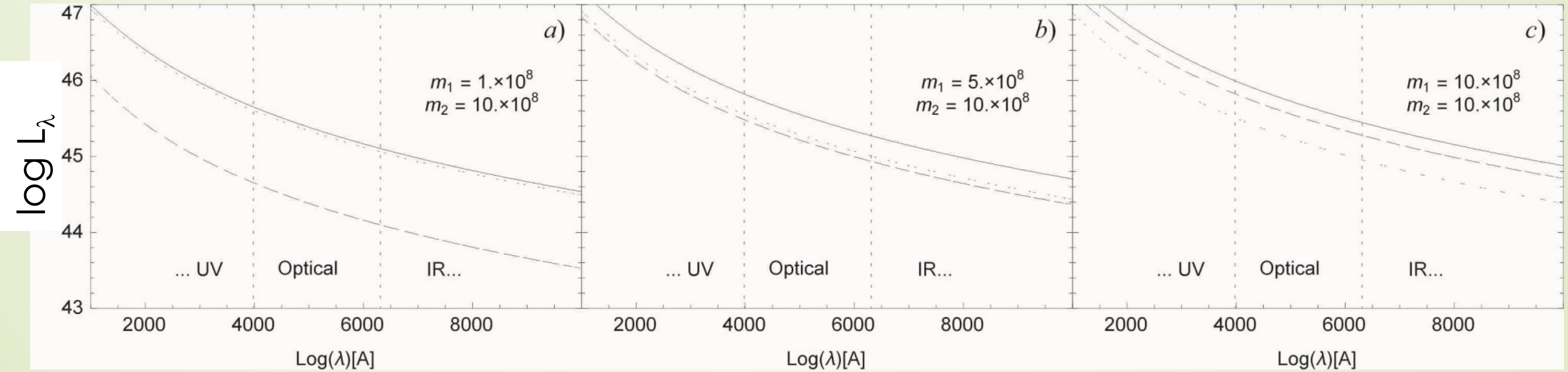
$$I_i(\lambda) = I_i(\lambda o) \times exp\left[-\left(\frac{\lambda - \lambda o(1 + z^i_{dopp})}{\sqrt{2}\sigma_i}\right)^2\right]\cos(\theta)$$

- In case of homogenous BLR we have:



Model and assumptions – binary system emission – kpc separation

- 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. Three images represent cases of different mass ratio,
  q = 0.1, q = 0.5 and q = 1.
- small mass – hard SED, big mass – soft SED.



Model and assumptions – subpc separation BLR limit justification

- However, it is very certain that parts of BLR closer to BH are more exposed to continuum radiation than the parts which are further away. This causes that re-emitted radiation has unequal distribution over the total BL region.
- Another important effect within this region is that BH together with the accretion disk can drag a part of BLR in orbit around center of mass of system.
- This is only present in a binary systems and could not be proposed with single BH AGNs.
- We suppose that inner part of BLR constrained by Roche lobe follow the orbital motion of the BH, and that the rest of the BL region is assumed to be stationary.

Model and assumptions – Roche lobes

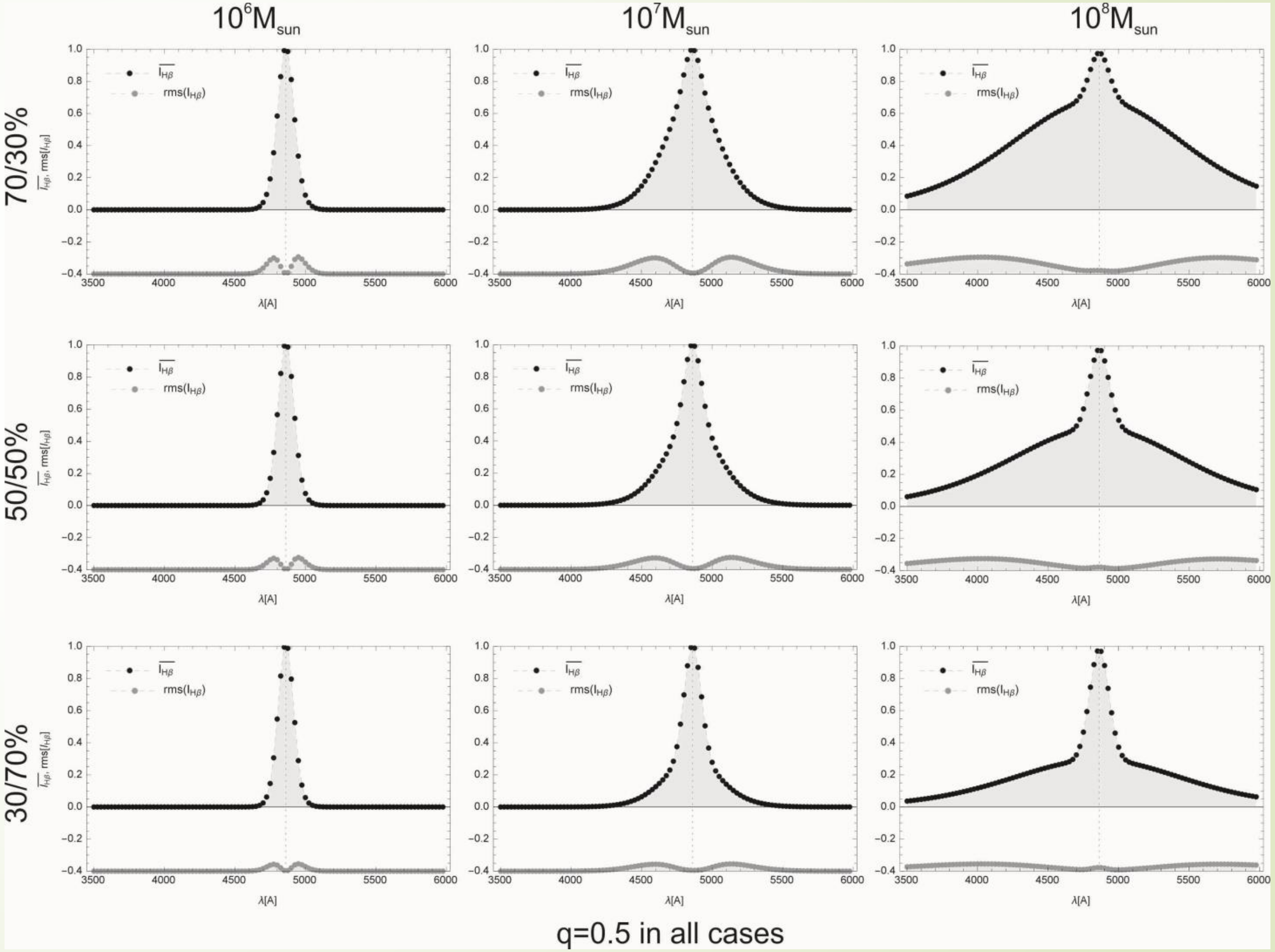
- Therefore, we compute Roche radius by using:

$$r_{roche}(t) = a(t)\frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1+q^{1/3})}$$

- where $a(t)$ is component separation during the orbit.
- We assume redistribution of emitted radiation from BLR region, for example: 70% of total BLR emission is from Roche BLRs and 30% is from circumbinary BLR. We also consider 50/50% or 30/70% cases.

Mean profile and *rms* value

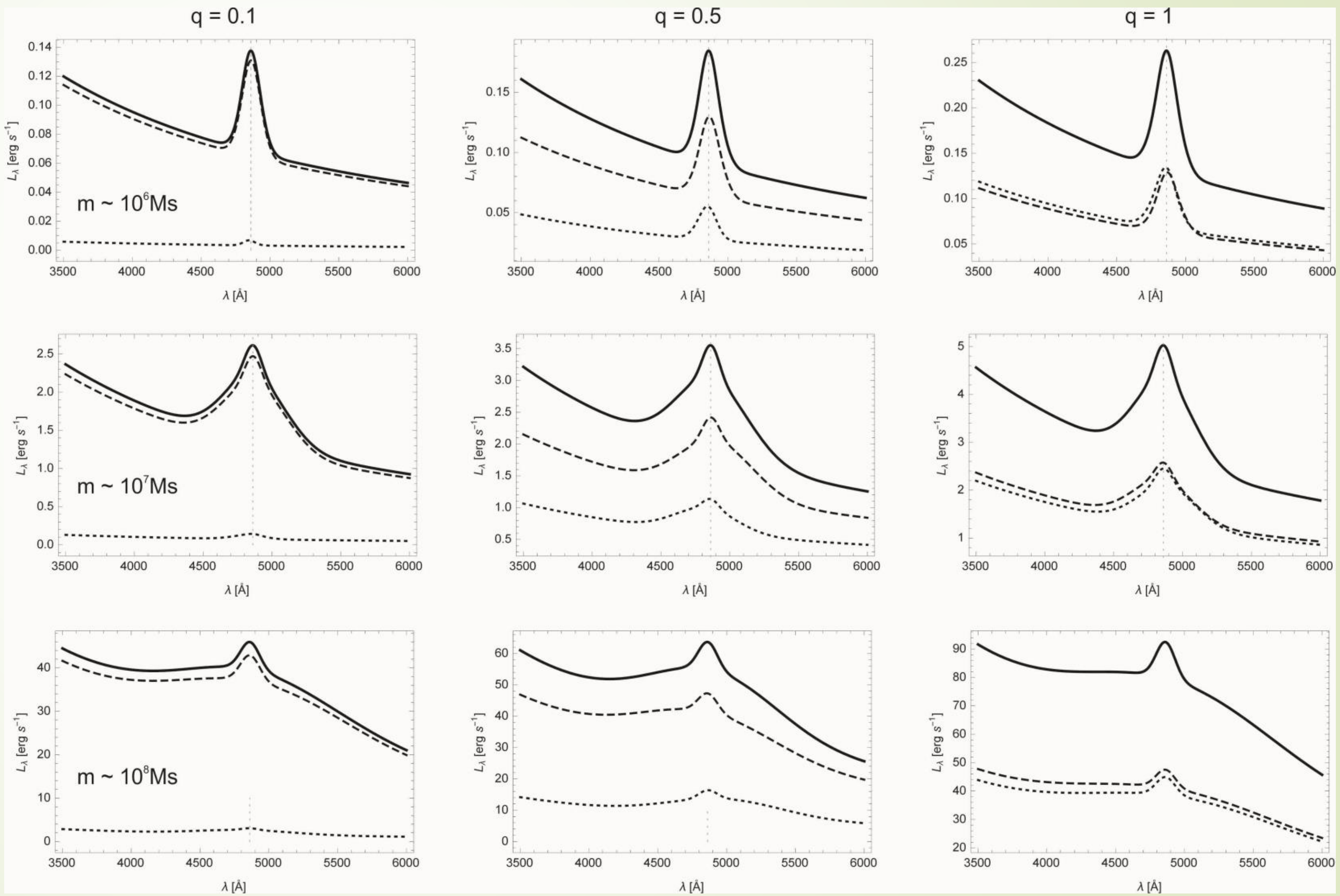
- Here we present results for given model in form of mean profile of combined Hβ line during the 4 full rotations of the system, for different orders of BH masses (10^6, 10^7, 10^8 M_{sun}).
- We propose 70%/30% luminosity distribution but tested different cases(50/50%, and 30/70%).
- Central parts are from circumbinary region, while wings originate from Roche limited BLR.
- We scaled to maximum intensities in order to compare line profiles
- With higher mass, lines are broader.
- *rms* is highest in case of luminous Roche lobe.



Combined Hβ line and continuum

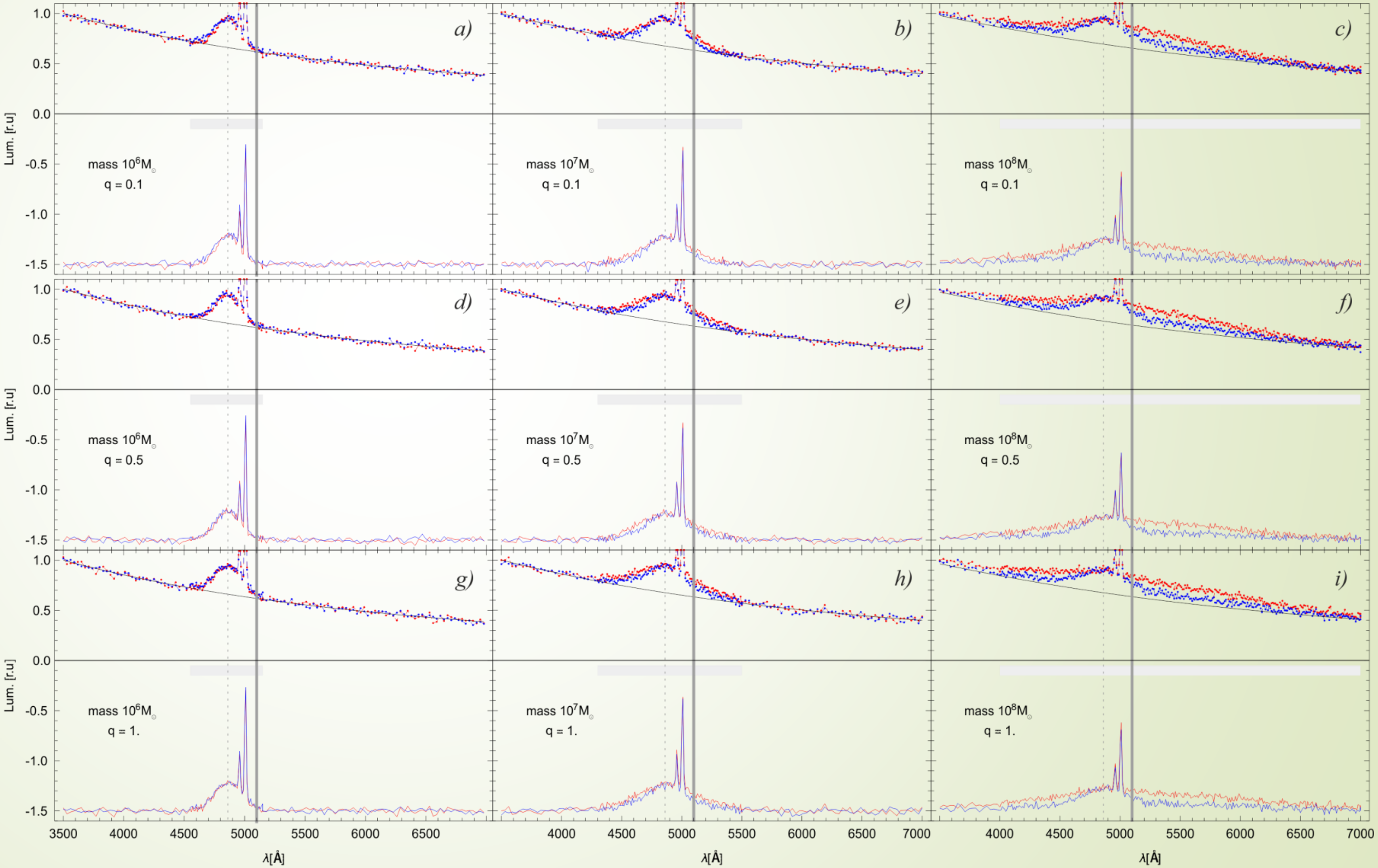
- Combined Hβ line from both components, superposed with the total continuum emission from both BHs.
- Different mass ratios are used q=0.1, 0.5,1 in cases of three orders of BH mass 10^6, 10^7, 10^8 M_{sun}.
- Such complex line could be created by at least two gaussian profiles, one broad coming from the Roche lobe and one narrow which originate from the rest of the BL region.
- Dynamics of the binary system can not produce line shift, but rather wobbling of line wings.

70/30% in all cases



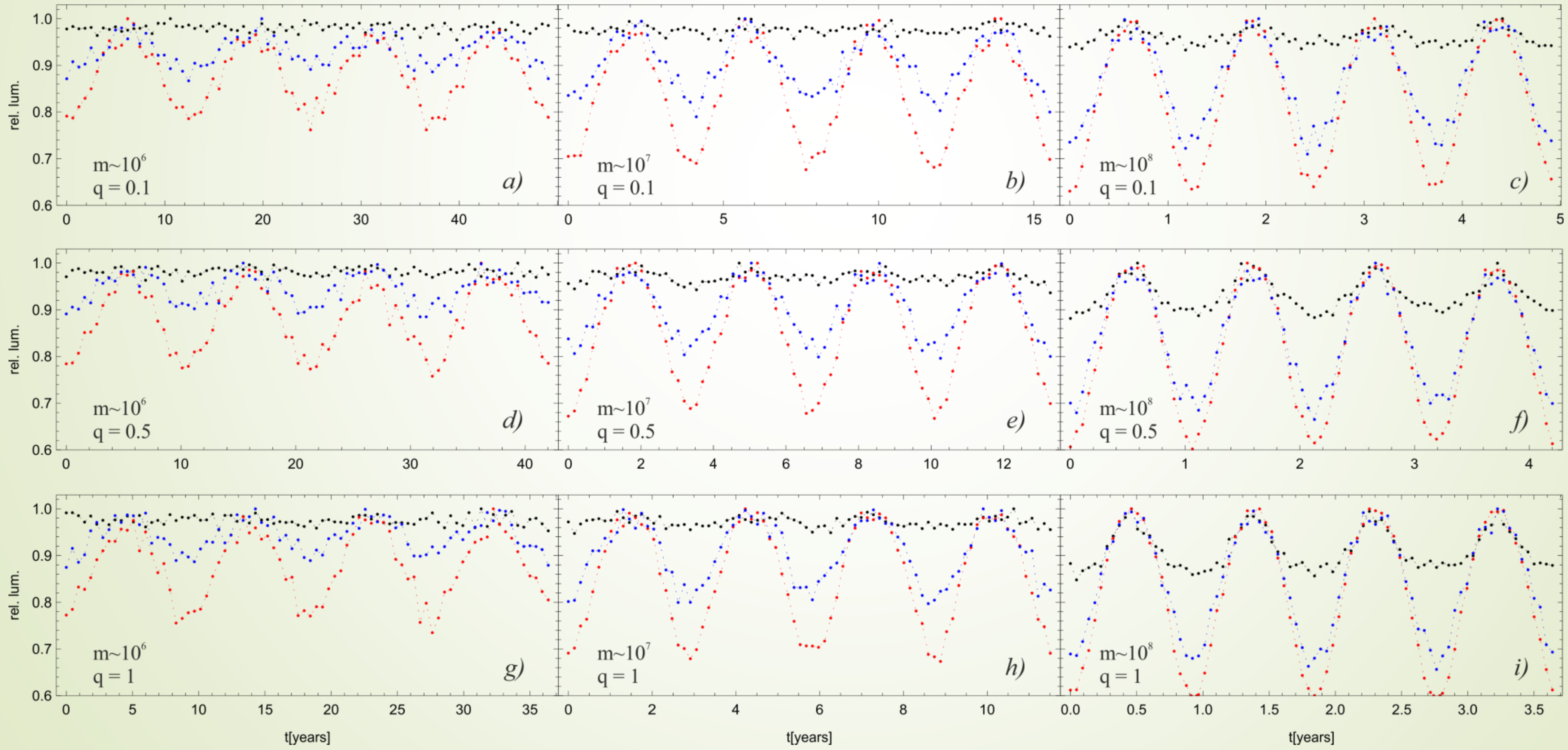
Continuum and line profile

- Hβ line profile for a particular moment during the orbit.
- OIII doublet (λ_a=4959A i λ_b=5007A) is for comparison purpose. White noise is added.
- Red and blue lines distinguish cases with different distribution of BLR emission (red 70/30% and blue 30/70%).
- There is a difference just in high mass cases.



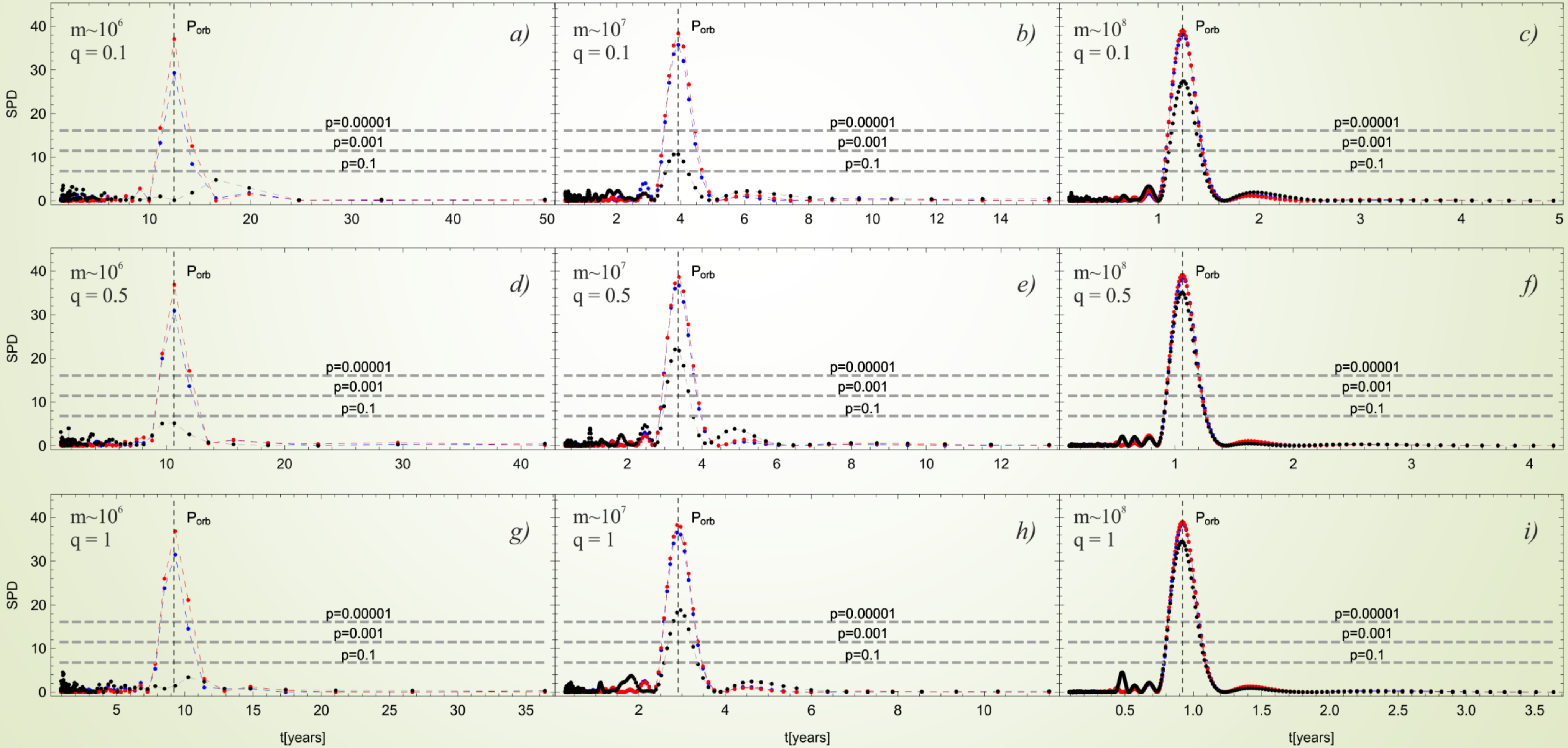
AGN structure – binary system - variability

- In case of previous configuration we computed variability during four full orbits. Black circles – continuum, red and blue – Hb line.
- Mass, mass ratio and separation dependence.
- Continuum variation depends on all three factors, line variation depends mostly on mass.



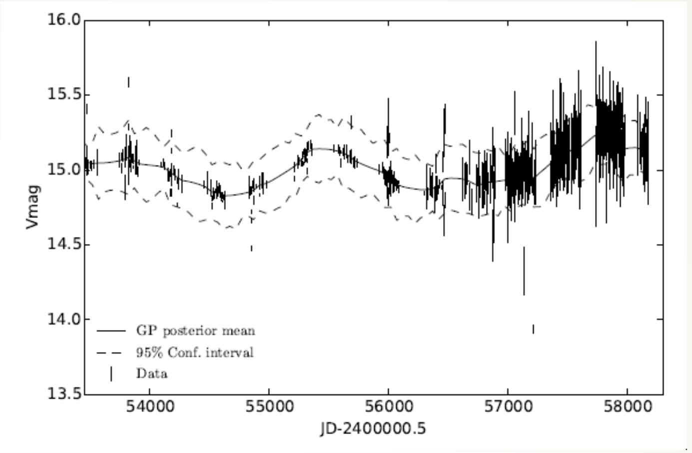
AGN structure – binary system

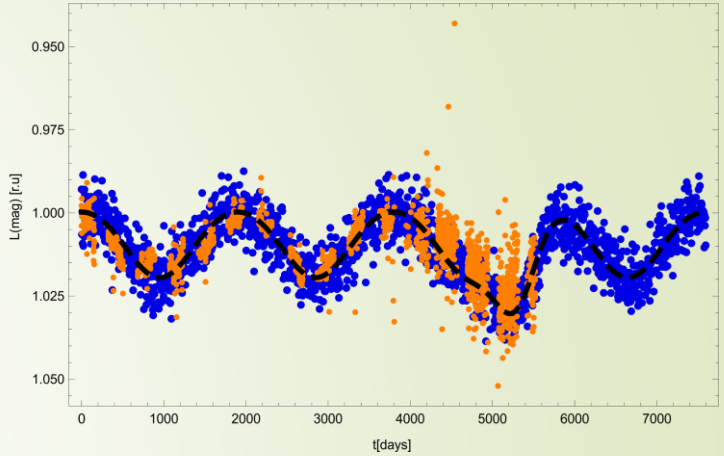
- Continuum (black dots) and Hb (red and blue dots) periodograms.
- Periodicity in continuum only for high mass systems.
- Line periodicity due to the Doppler shift.

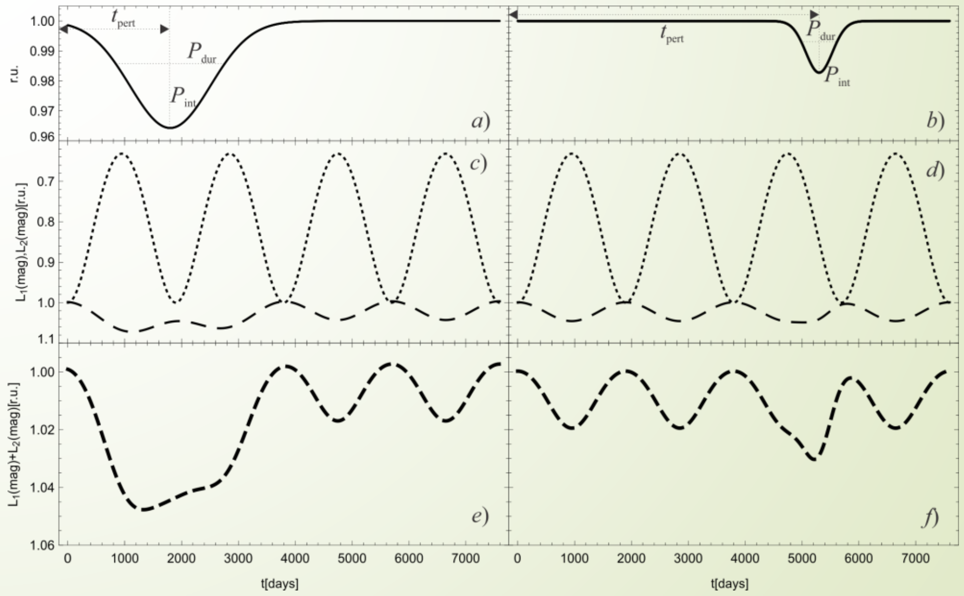


AGN structure – case of PG1302-102 variability

- We apply similar model to explore observed variability in PG1302-102 system.
- We assume binary system with q=0.1
- We propose an artificial temperature perturbation of the disk.







Kovačević, et. al., ApJ, 2019.

Conclusions

- In subparsec supermassive binary systems variability could be observed in line and continuum spectra.
- In case of Hb line variations are present mostly in line wings, rather than in it's center.
- In continuum variability is present in high mass case and not for low masses.

Thank you