Possible Observational Signatures of Supermassive Black Hole Binaries in Their Fe Kα Line Profiles

P. Jovanović[1], V. Borka Jovanović[2], D. Borka[2] and L. Č. Popović[1]

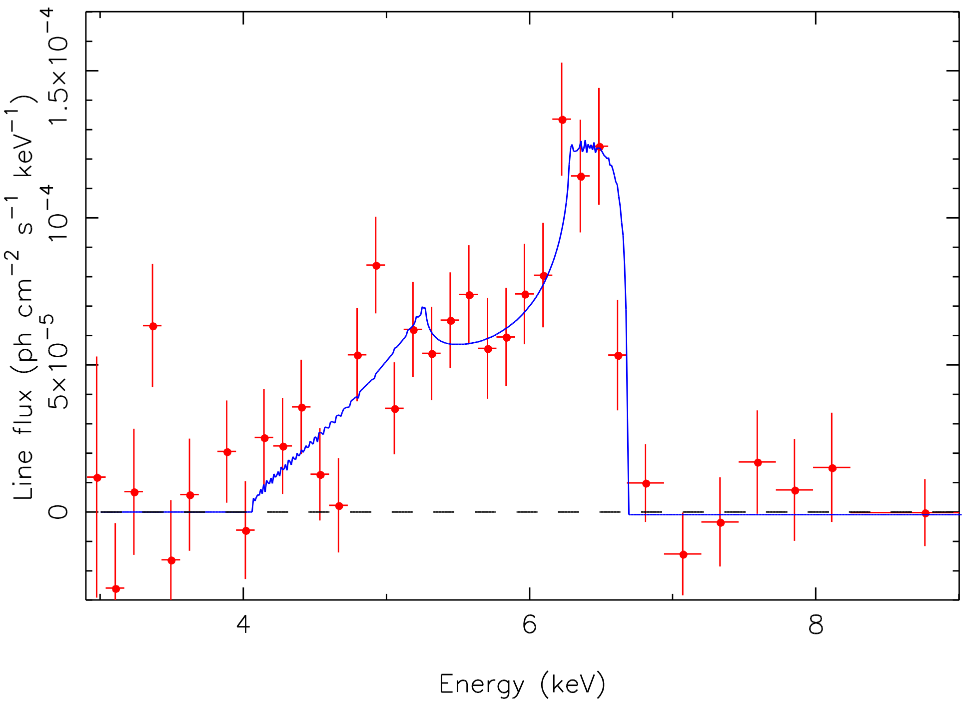
[1]Astronomical Observatory Belgrade, Serbia

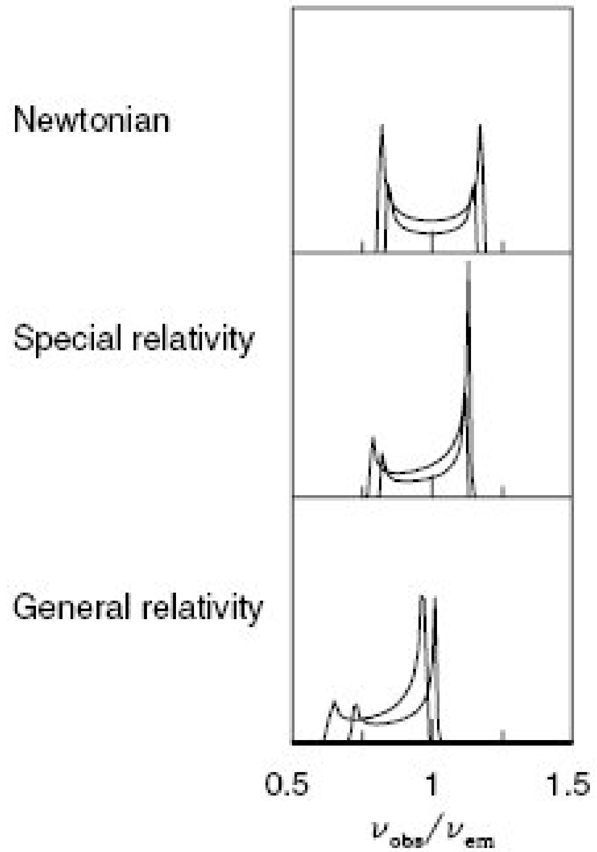
[2]Atomic Physics Laboratory (040), Vinča Institute of Nuclear Sciences, University of Belgrade, Serbia

Outline

- Relativistically broadened Fe Kα spectral line emitted from accretion disks around single and binary supermassive black holes (SMBHs)
- Simulations of the X-ray radiation from a relativistic accretion disk based on ray-tracing in Kerr metric
- Supermassive black hole binaries (SMBHBs) and their models
- Keplerian barycentric orbits of SMBHBs
- Influence of Doppler shifts due to orbital motion on the observed line profiles
- Results
  - Variability of the line profiles and fluxes for different:
    - disk parameters
    - orbital elements of a SMBHB
    - mass ratios between the SMBHB components
    - positions and widths of an empty gap in the disk around primary SMBH
  - Detectability of SMBHB signatures in the observed Fe Kα line profiles
- Conclusions

Relativistically broadened Fe Kα line

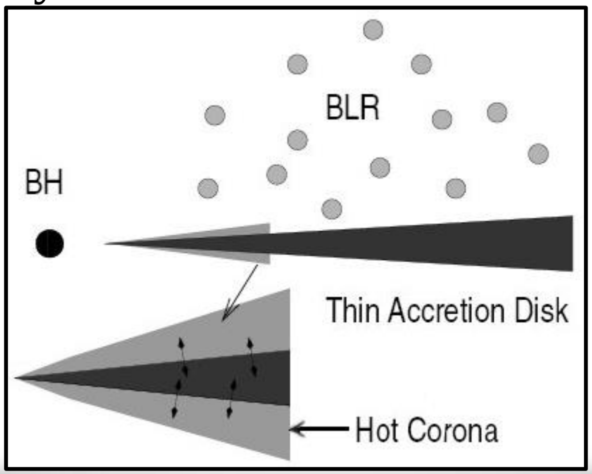




Fabian, A. C. 2006, AN, 327, 943

The Fe Kα line from MCG-6-30-15 (Seyfert I) observed by the ASCA (Tanaka et al, 1995, *Nature*, **375**, 659) and the modeled by a disk around a Schwarzschild BH

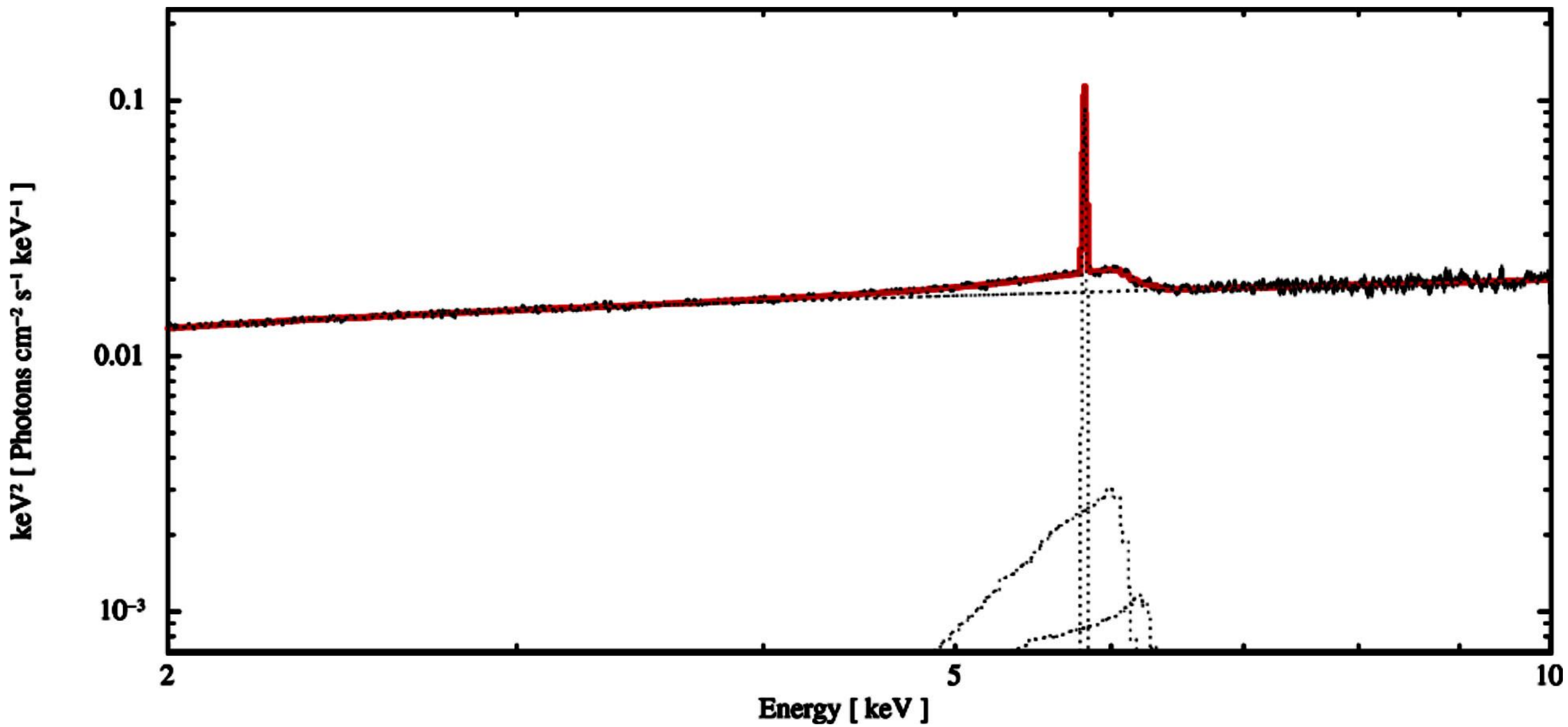
- Line width corresponds to:
  v ~ 100.000 km/s (MCG-6-30-15)
  v ~ 48.000 km/s (MCG-5-23-16)
  v ~ 20.000 – 30.000 km/s
  (many other AGN)



- **Line production**: hot corona sandwiching a relatively cold disk irradiates it by the hard X-ray power law continuum, causing photoelectric absorption followed by fluorescent line emission at 6.4 keV

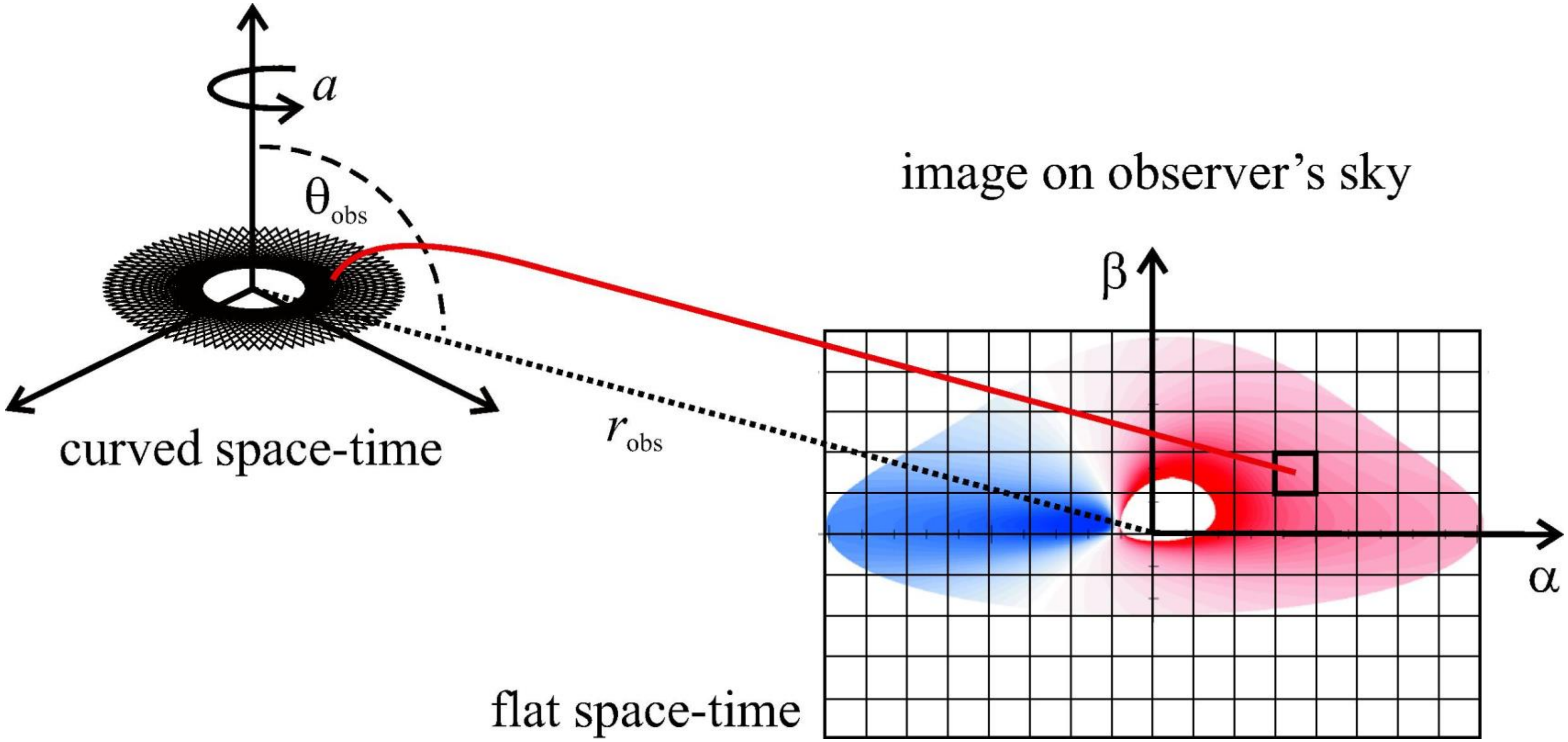
Double (composite) relativistic Fe Kα lines

- Double relativistic Fe Kα lines and periodic X-ray variability are expected to be detected from very massive ($> 10^8\ M_\odot$) cosmologically nearby ($z_{cosm} < 1$) black hole binaries (Sesana, et al, 2012, MNRAS, 420, 860)



A simulated X-ray spectrum from a very massive black hole binary (Sesana, et al, 2012, MNRAS, 420, 860): two relativistic Fe Kα lines, in addition to a Gaussian narrow line emitted from material at much larger radii, and power law continuum with spectral index $\Gamma \sim 1.8$

Ray tracing in Kerr metric



- Power law surface emissivity of the disk:

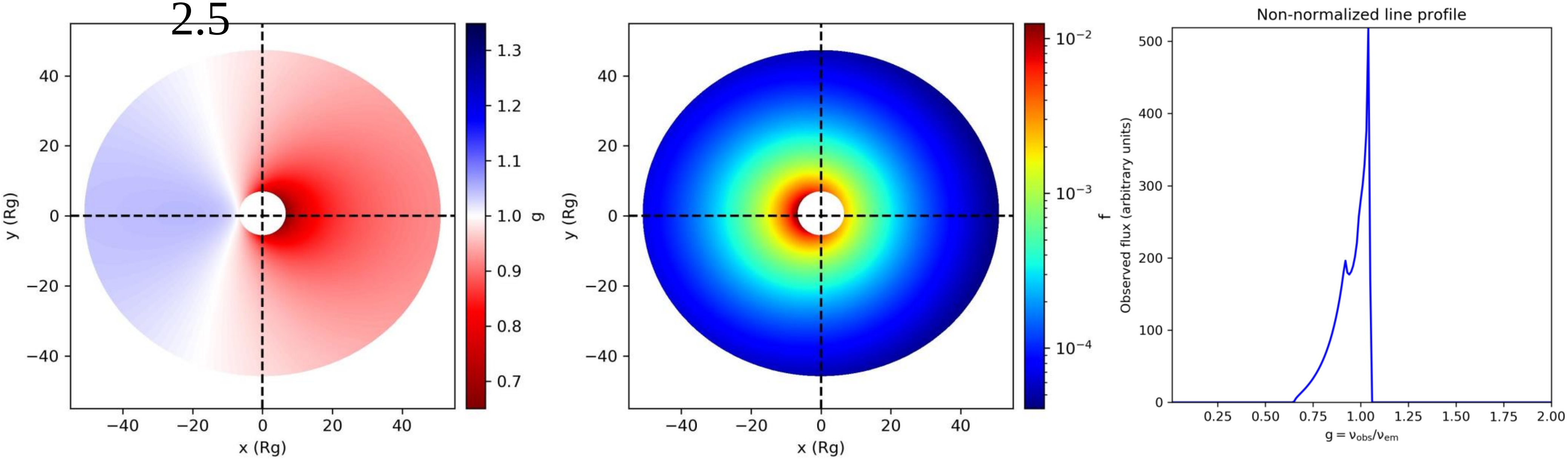
$$\boxed{\varepsilon(r) = \varepsilon_0 \cdot r^p}$$

$$\left.\begin{aligned} \alpha &= -\frac{\lambda}{\sin\theta_{obs}} \\ \beta &= \pm\sqrt{q^2 + a^2\cos^2\theta_{obs} - \lambda^2\cot^2\theta_{obs}} \end{aligned}\right\} \Rightarrow \lambda, q \Rightarrow \pm \int_{r_{em}}^{\infty} \frac{dr}{\sqrt{R(r,\lambda,q)}} = \pm \int_{\theta_{em}}^{\theta_{obs}} \frac{d\theta}{\sqrt{\Theta(\theta,\lambda,q)}}$$

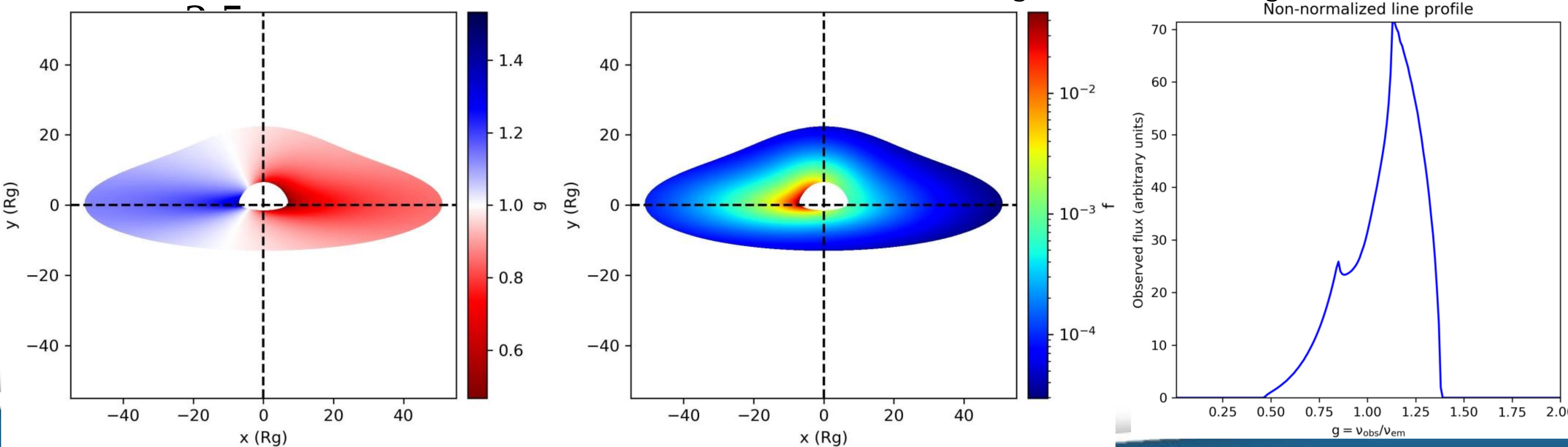
- Simulated line: $$\boxed{F_{obs}(E_{obs}) = \int_{image} \varepsilon(r) g^4 \delta(E_{obs} - gE_0)\, d\Xi, \qquad g = \frac{E_{obs}}{E_{em}}}$$

Disk models

1. ***Disk 1***: $a = 0.1$, $i = 25^{o}$, $R_{in} = R_{ms} = 5.67\ R_g$, $R_{out} = 50\ R_g$, $p = -2.5$



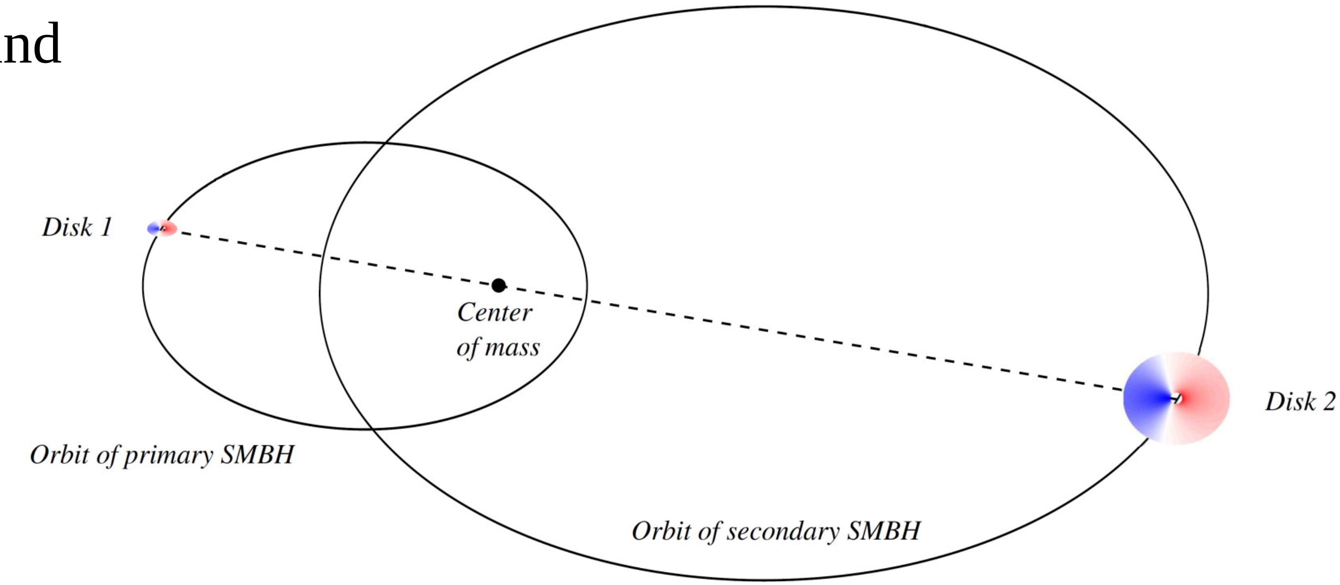
2. ***Disk 2***: $a = 0.1$, $i = 75^{o}$, $R_{in} = R_{ms} = 5.67\ R_g$, $R_{out} = 50\ R_g$, $p = -2.5$



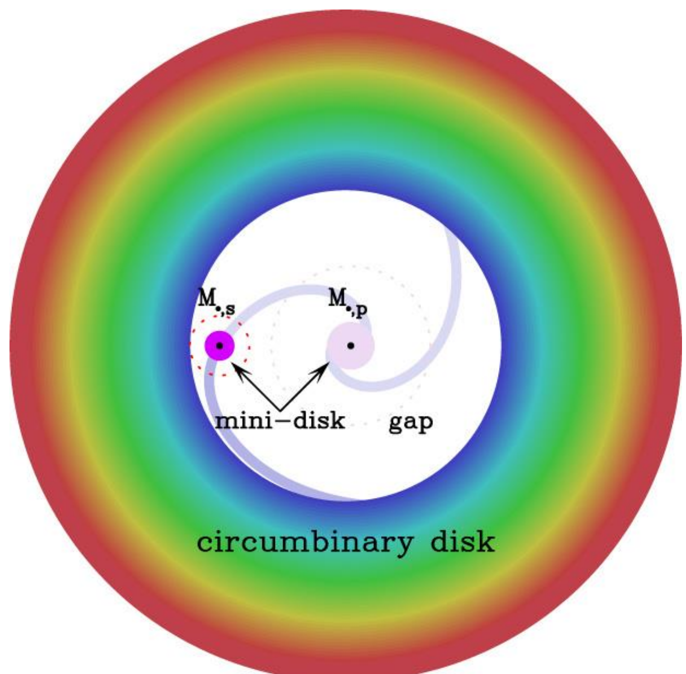
SMBHB models

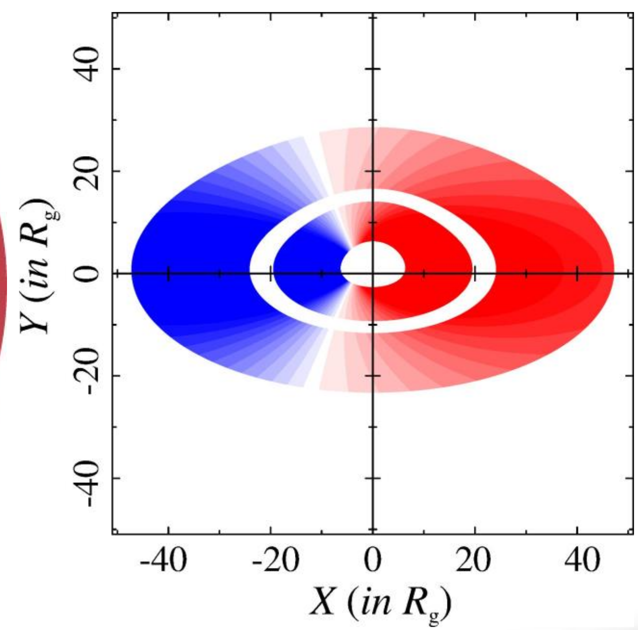
1. ***Model 1***: accretion disks around both primary and secondary SMBHs contribute to their composite line emission (e.g. SDSS 153636.22+044127.0)

(Boroson & Lauer, 2009. Nature, 458, 53)



2. ***Model 2***: the secondary SMBH is embedded in the accretion disk around primary, causing an empty gap in the disk (e.g. Mrk 231)

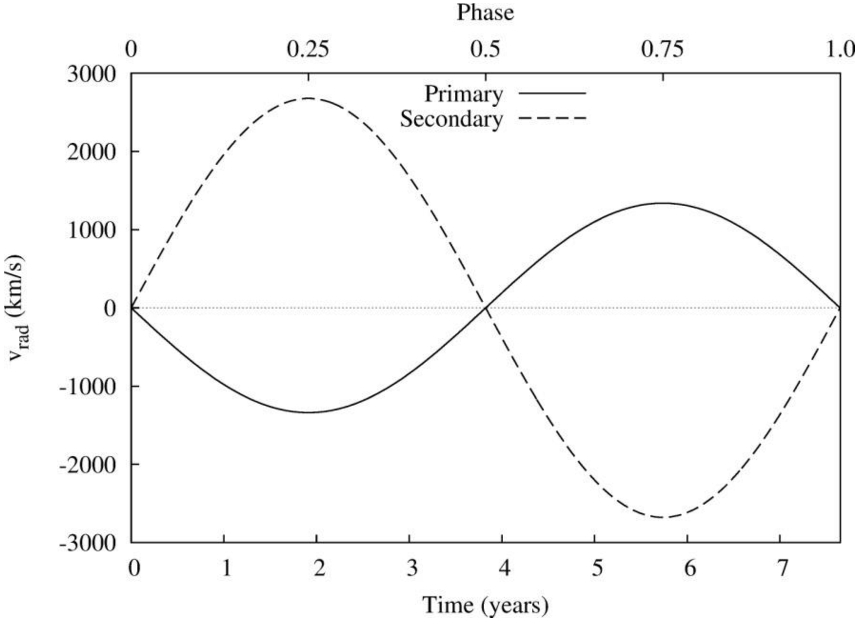


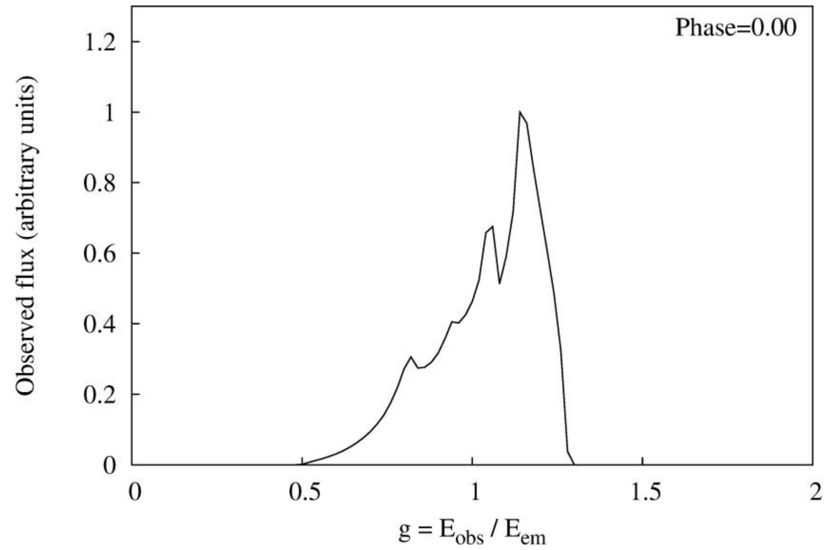


Yan et al. 2015. ApJ, 809, 117

Some previous results

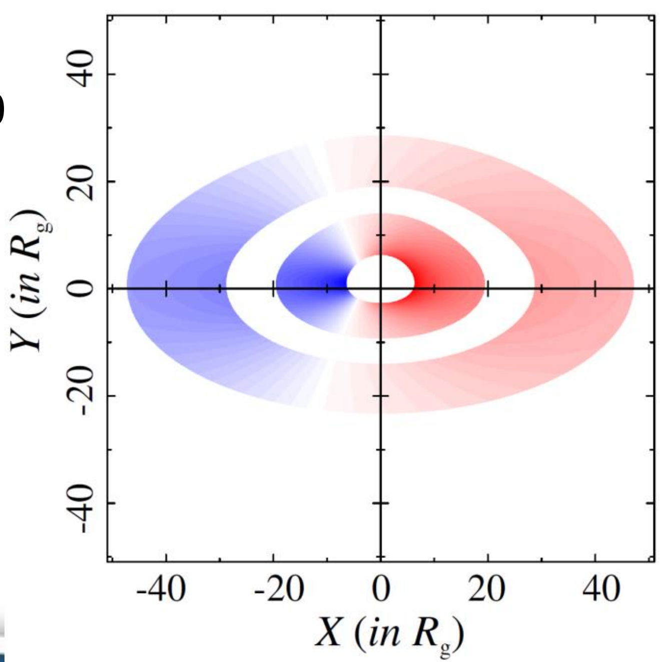
- Composite line profiles: $F\left(g\right)=F_1\left(\left[\frac{1}{g}-\frac{V_1^{rad}}{c}\right]^{-1}\right)+F_2\left(\left[\frac{1}{g}-\frac{V_2^{rad}}{c}\right]^{-1}\right)$

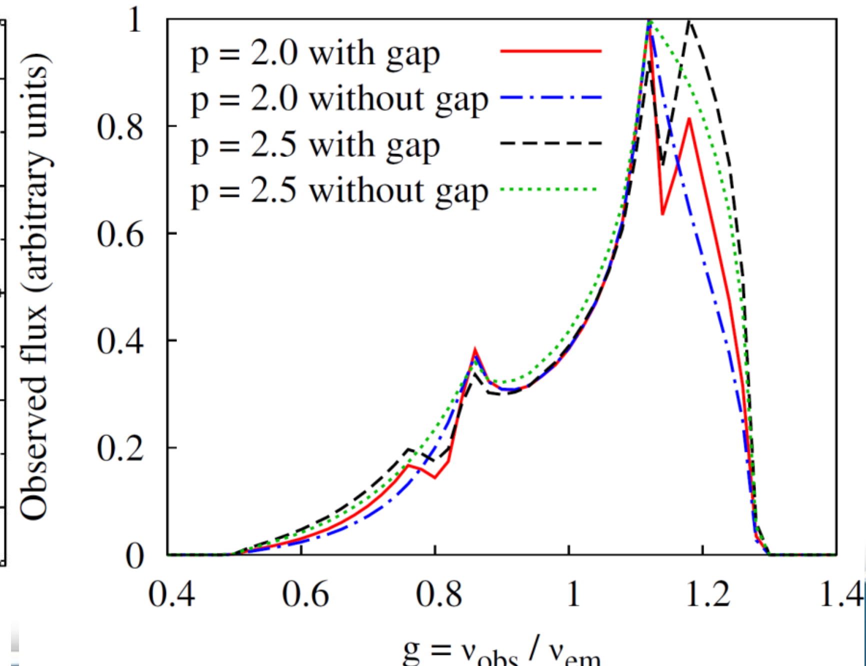




Jovanović, Borka Jovanović, Borka, Bogdanović, 2014. AdSpR, 54, 1448

An accretion disk (i = 60°) with an empty gap between 20 and 30 R_g, and the profiles of the Fe Kα line emitted from the disk with and without the gap for two different power law emissivity indices p (Jovanović, Borka Jovanović, Borka, 2014. Proc. of the 27th SPIG, 485)





Keplerian barycentric orbits of SMBHBs

1. The third Kepler's law ⇒ orbital period: $P^2 = \frac{4\pi^2 a^3}{G\,(1+q)\,M_1}, \quad q = \frac{M_2}{M_1}$
2. Mean anomaly: $M = \frac{2\pi}{P}\,(t-\tau) = 2\pi\Phi,$ where Φ is orbital phase
3. Kepler's Equation: $M = E - e\sin E \Rightarrow$ eccentric anomaly $E \Rightarrow$
4. True anomaly: $\theta = 2\arctan\left(\sqrt{\frac{1+e}{1-e}}\tan\frac{E}{2}\right)$
5. True barycentric orbits in the orbital plane (their orientations differ by 180°):

$$r_{1,2}\,(\theta) = \frac{a_{1,2}\,(1-e^2)}{1+e\cos\theta}, \quad a_1 = \frac{q\,a}{1+q}, \quad a_2 = \frac{a}{1+q}$$

6. Their corresponding apparent orbits on the observer's sky plane:

$$x_{1,2} = r_{1,2}\cos\theta\,[\cos\Omega\cos\omega - \sin\Omega\sin\omega\cos i] + r_{1,2}\sin\theta\,[-\cos\Omega\sin\omega - \sin\Omega\cos\omega\cos i]$$
$$y_{1,2} = r_{1,2}\cos\theta\,[\sin\Omega\cos\omega + \cos\Omega\sin\omega\cos i] + r_{1,2}\sin\theta\,[-\sin\Omega\sin\omega + \cos\Omega\cos\omega\cos i]$$

7. Radial velocities of the components and their velocity semiamplitudes:

$$V_{1,2}^{rad}\,(\theta) = K_{1,2}\,[\cos(\theta+\omega) + e\cdot\cos\omega] + \gamma, \quad K_{1,2} = \frac{2\pi a_{1,2}\sin i}{P\sqrt{1-e^2}},$$

where γ is systemic velocity

Influence of Doppler shifts on the observed disk emission

- Redshift factor due to relativistic effects: $g = \dfrac{E_{obs}}{E_{em}} = \dfrac{1}{1+z}$
- Redshift factors due to radial velocities of the components (Doppler shifts):

$$g_{1,2} = \frac{1}{1+z_{1,2}}, \quad z_{1,2} \approx \frac{V_{1,2}^{rad}}{c}, \quad \mathrm{V}_{1,2}^{rad} \ll c$$

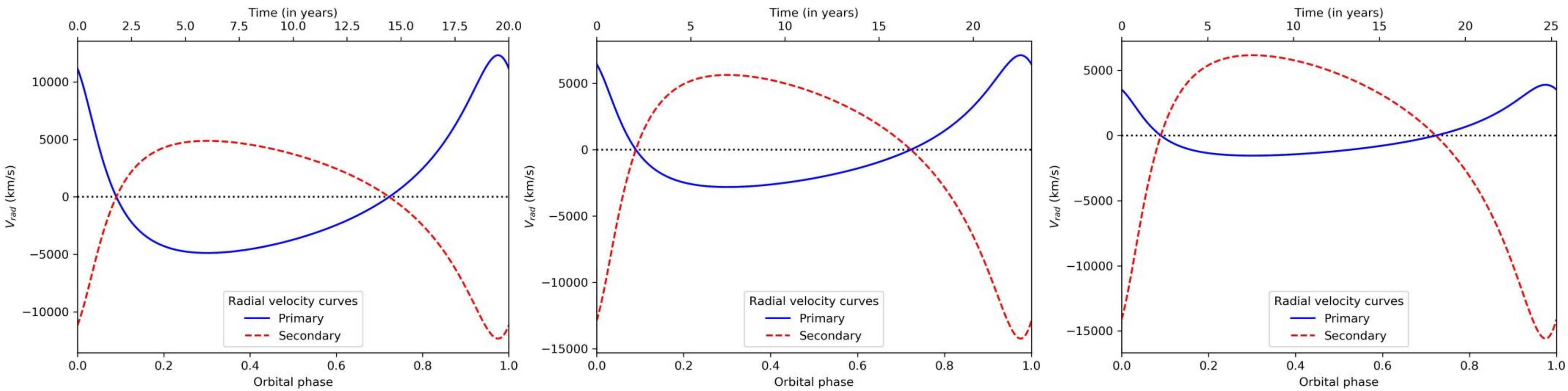
- Total redshift factor: $g_{tot} = \dfrac{1}{1+z+z_{12}} = \dfrac{1}{\dfrac{1}{g} + \dfrac{1}{g_{1,2}} - 1}$

Assumed SMBHB parameters and orbital elements

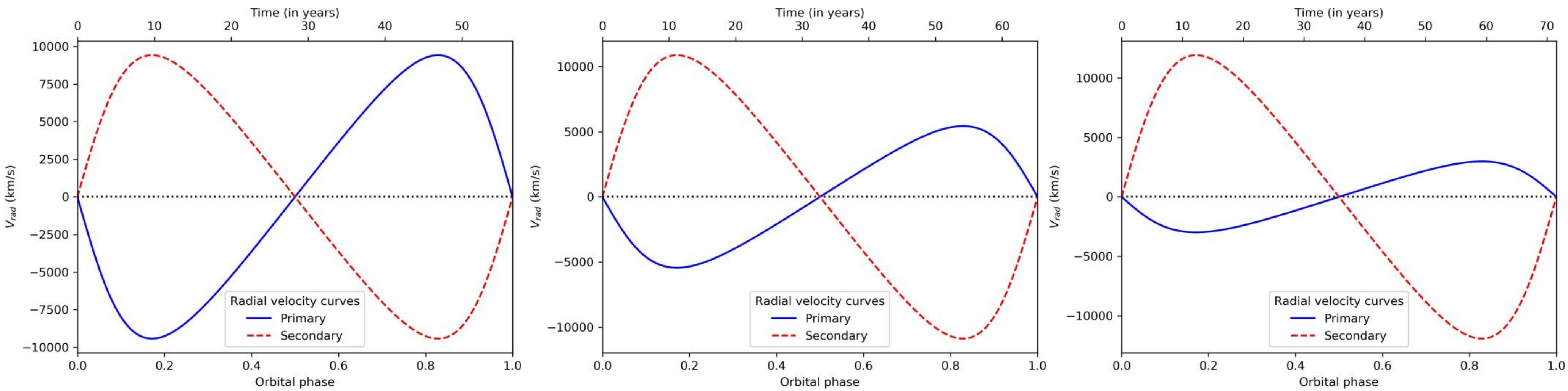
- Angular diameter distance to SMBHB: D_A = 10 Mpc $(z_{cosm} \approx 0.0023)$
- Mass of the primary SMBH: $M_1 = 10^{10}\ M_\odot$
- Outer radius of the disk around the primary: $R_{out} = 50\ R_g \approx 5000\ \mathrm{AU} \approx 500\ \mu\mathrm{as}$
- A very close and massive SMBHB ⇒ large apparent size of a disk on the observer's sky (1 mas × 1 mas)

Orbital elements	a (AU)	a (pc)	Period (yr) $q_1 = 1.0$	Period (yr) $q_2 = 0.5$	Period (yr) $q_3 = 0.25$	e	i (°)	Ω (°)	ω (°)	γ (km/s)
orbit 1	2×10^4	0.1	20.0	23.1	25.3	0.5	30	0	30	0
orbit 2	4×10^4	0.2	56.6	65.3	71.6	0.25	60	0	90	0

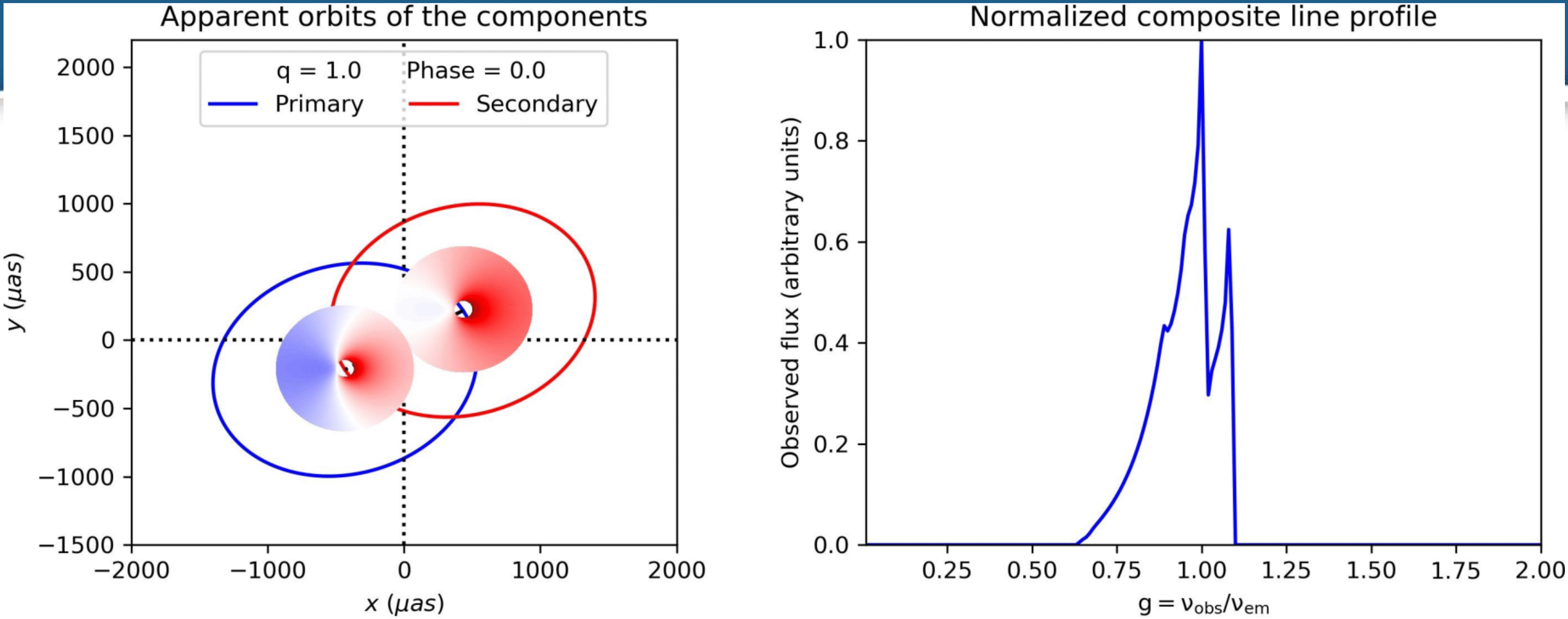
Results: radial velocities



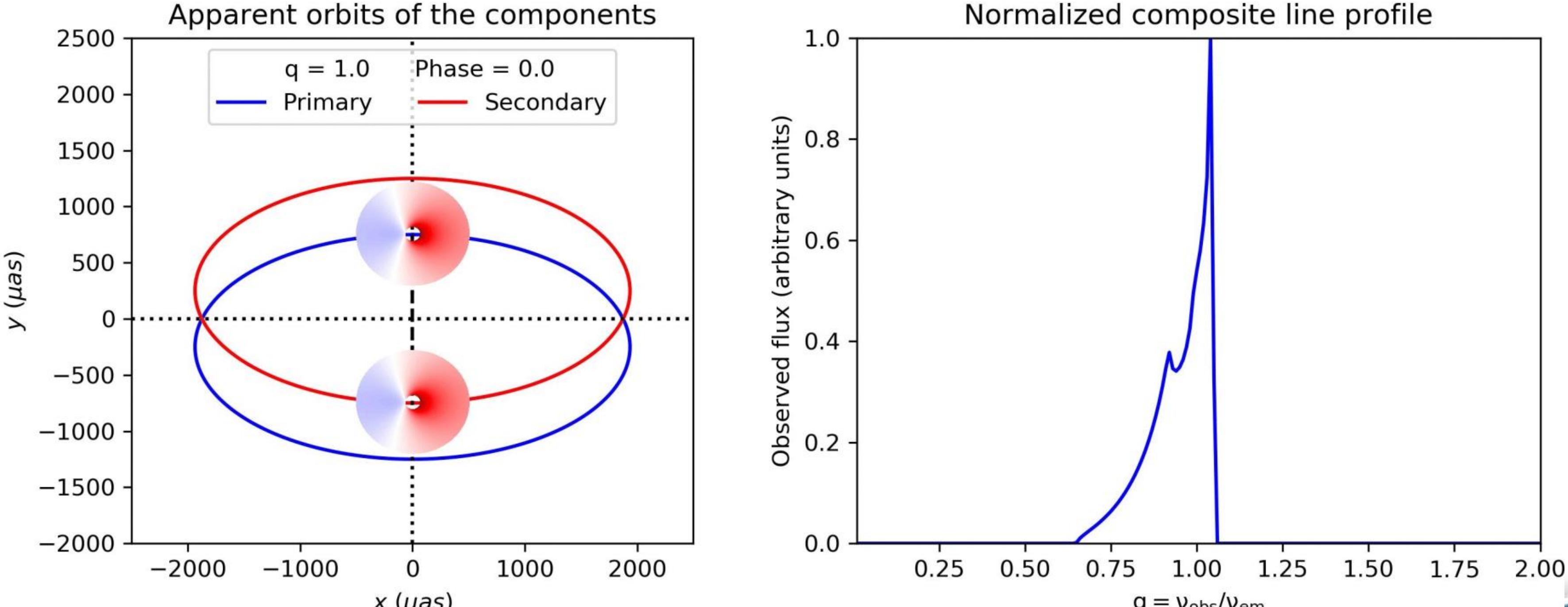
Radial velocities of the components for orbit 1 and for q = 1, 0.5, 0.25, respectively



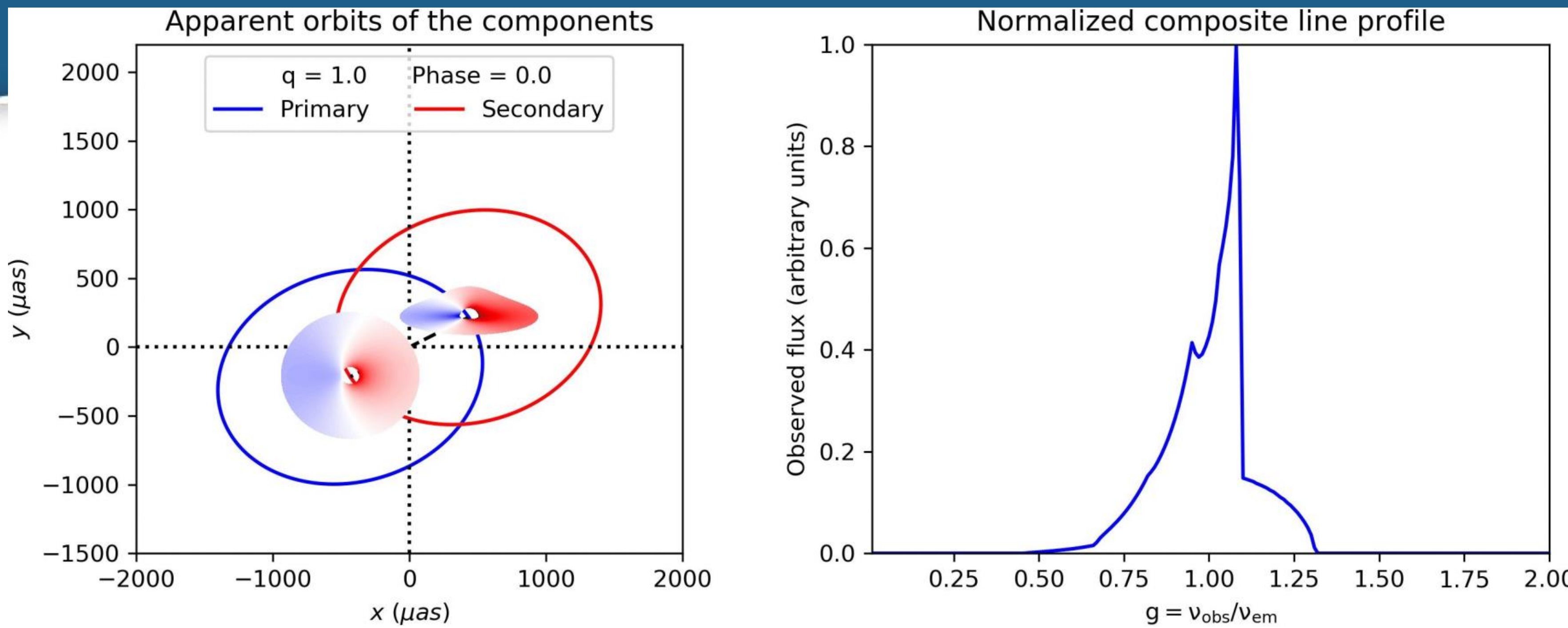
The same as above, but for orbit 2



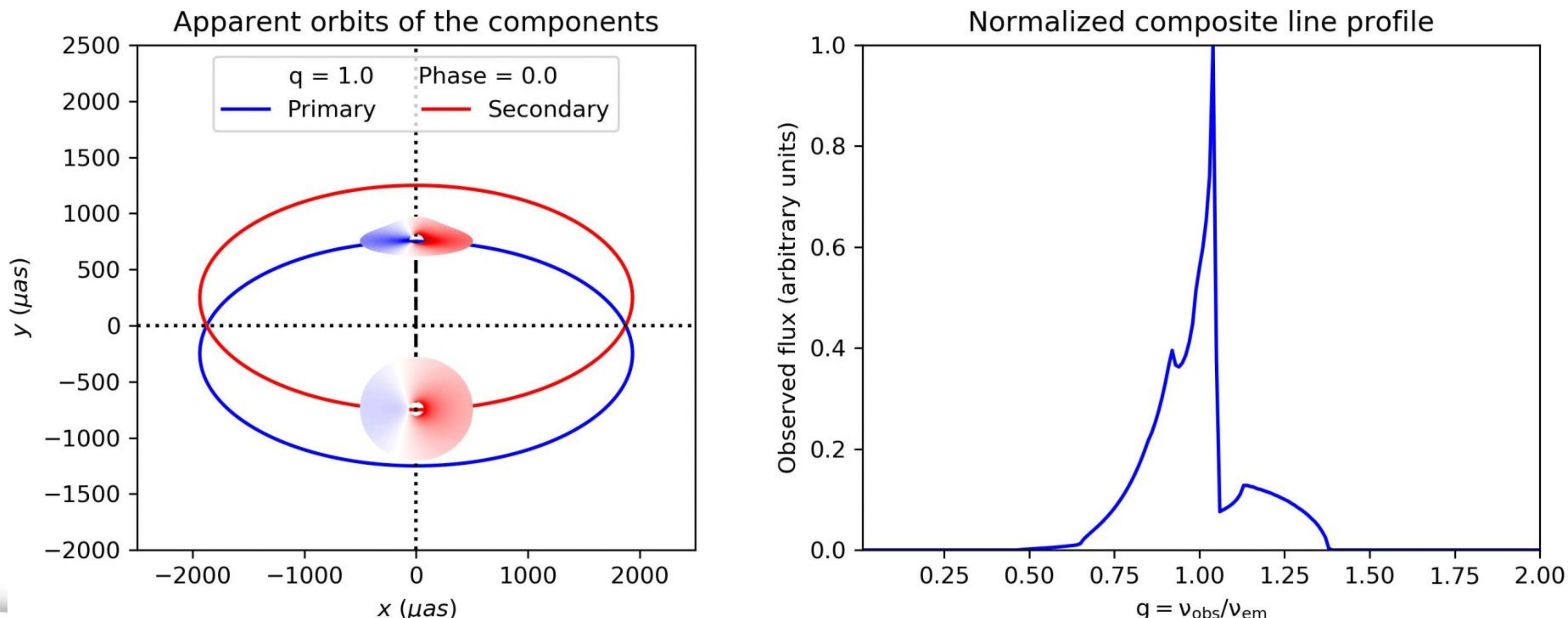
Case 1: SMBHB during different phases of orbit 1, for disk 1 around both primary and secondary and for $q = 1$ (left), as well as the corresponding composite Fe Kα line profiles (right)



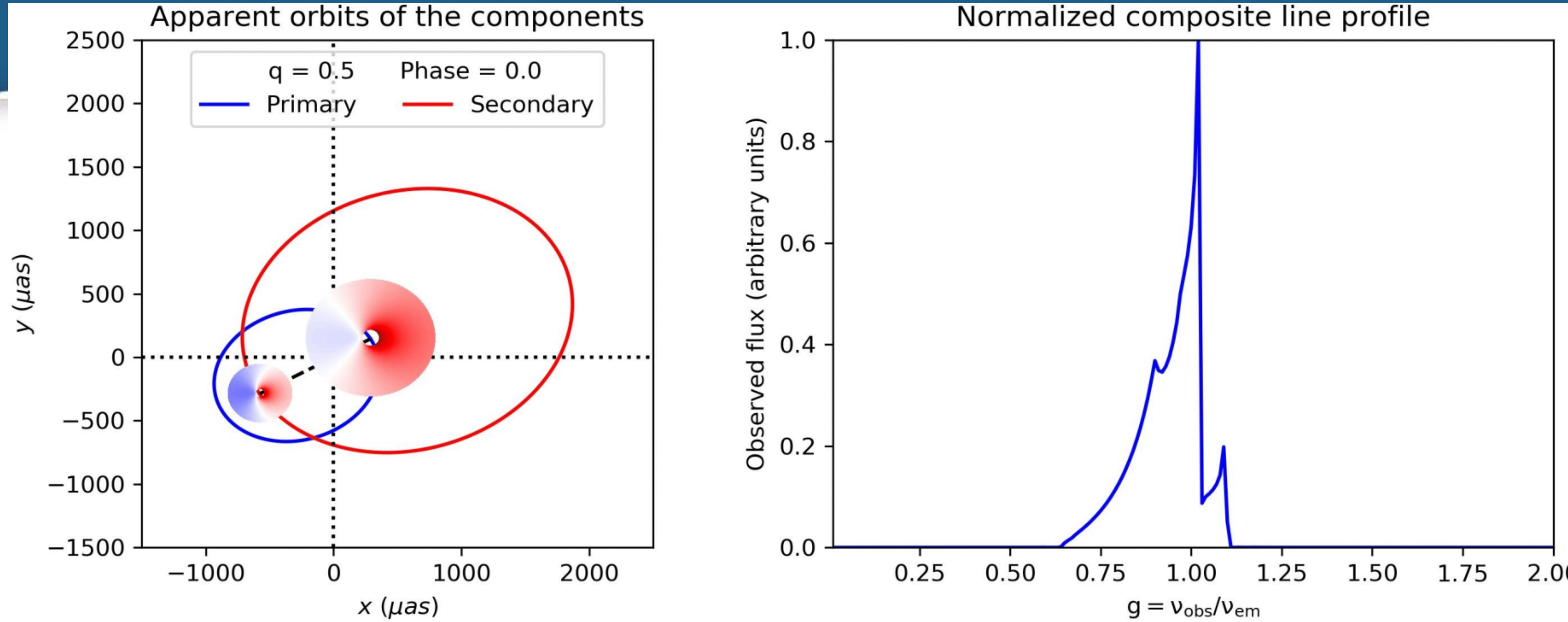
Case 2: The same as above, but for orbit 2



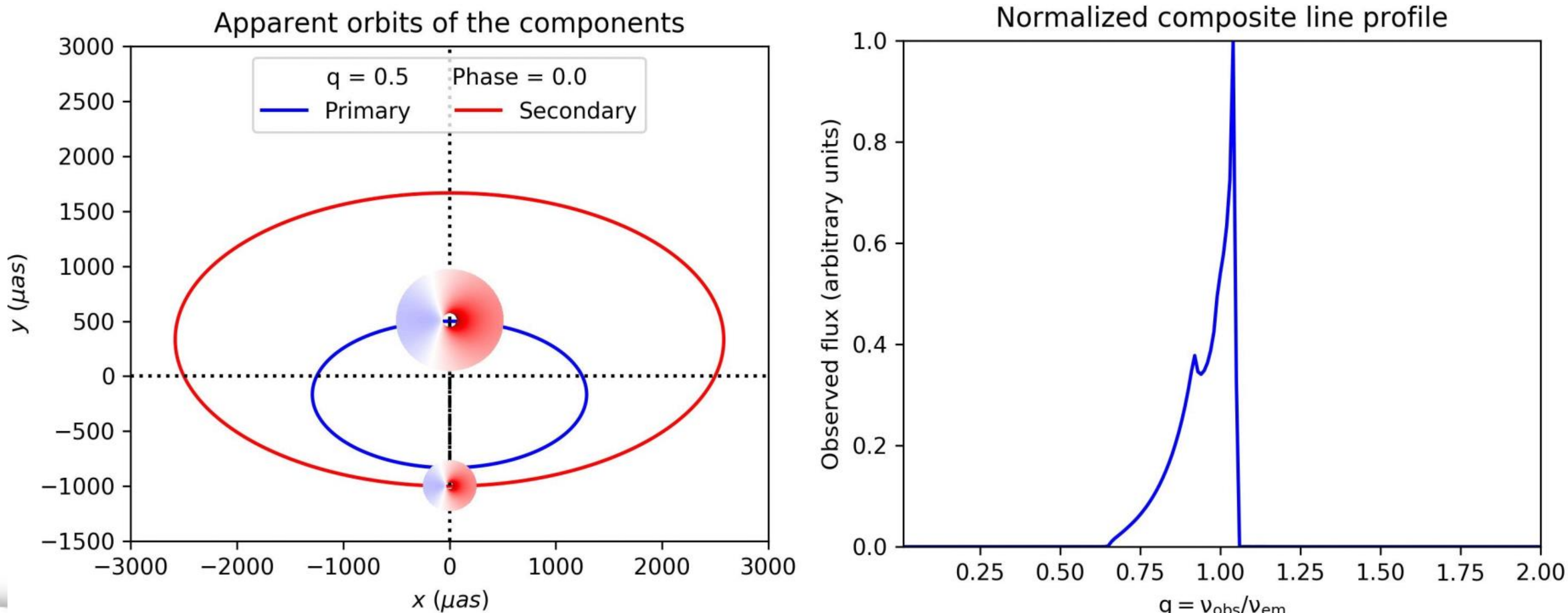
Case 3: SMBHB during different phases of orbit 1, for disk 2 around primary, disk 1 around secondary and for $q = 1$ (left), as well as the corresponding composite Fe Kα line profiles (right)



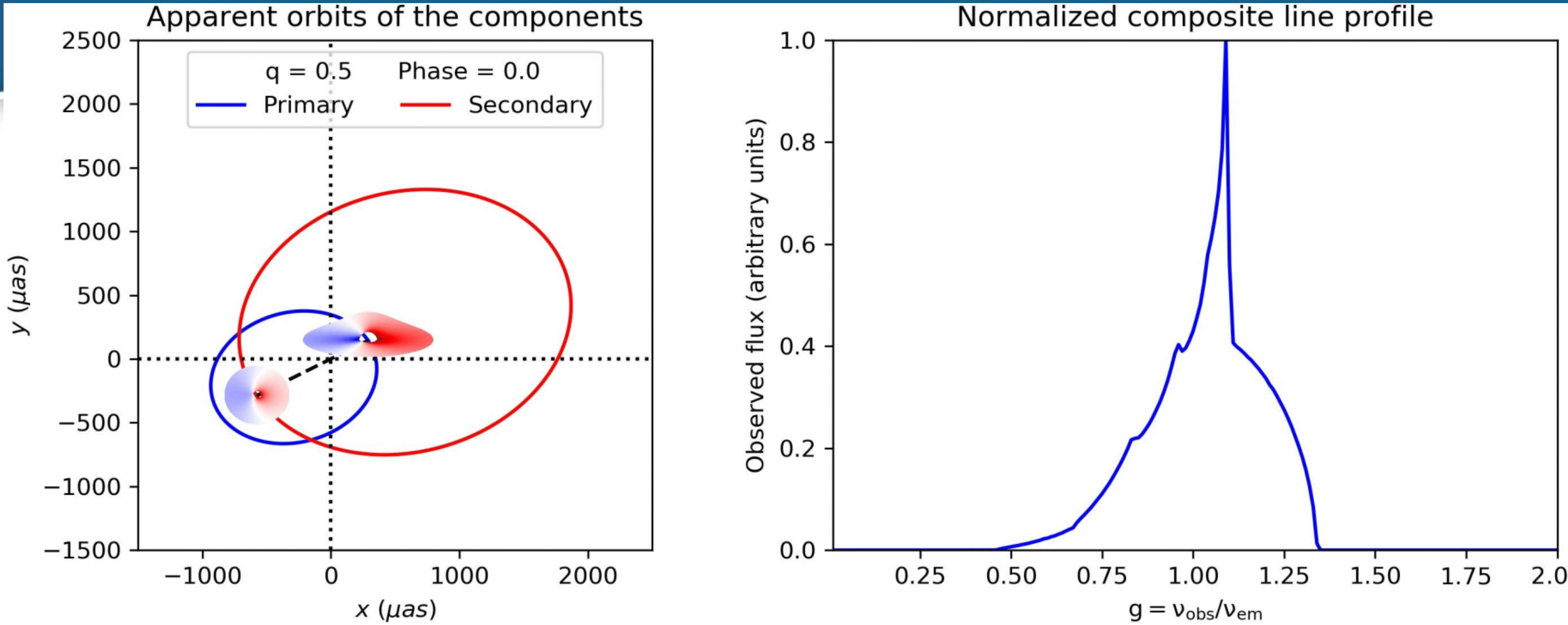
Case 4: The same as above, but for orbit 2



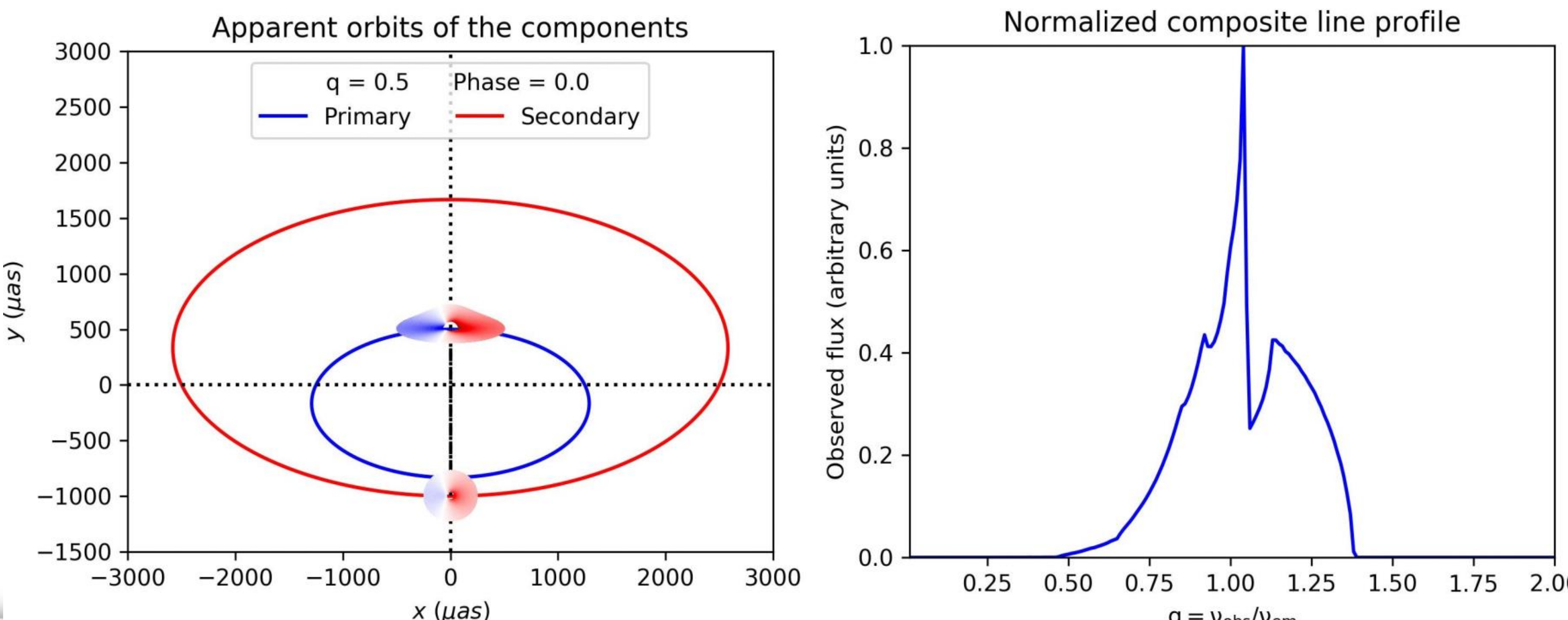
Case 5: SMBHB during different phases of orbit 1, for disk 1 around both primary and secondary and for q = 0.5 (left), as well as the corresponding composite Fe Kα line profiles (right)



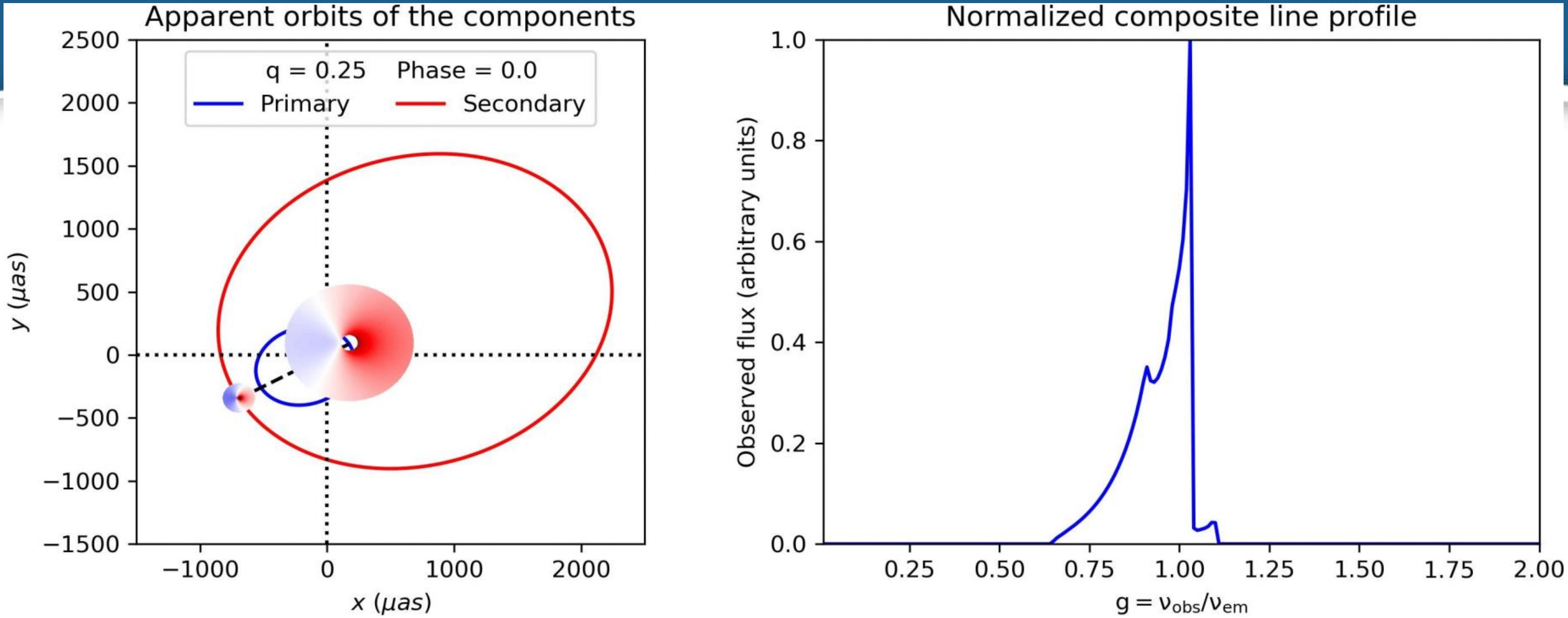
Case 6: The same as above, but for orbit 2



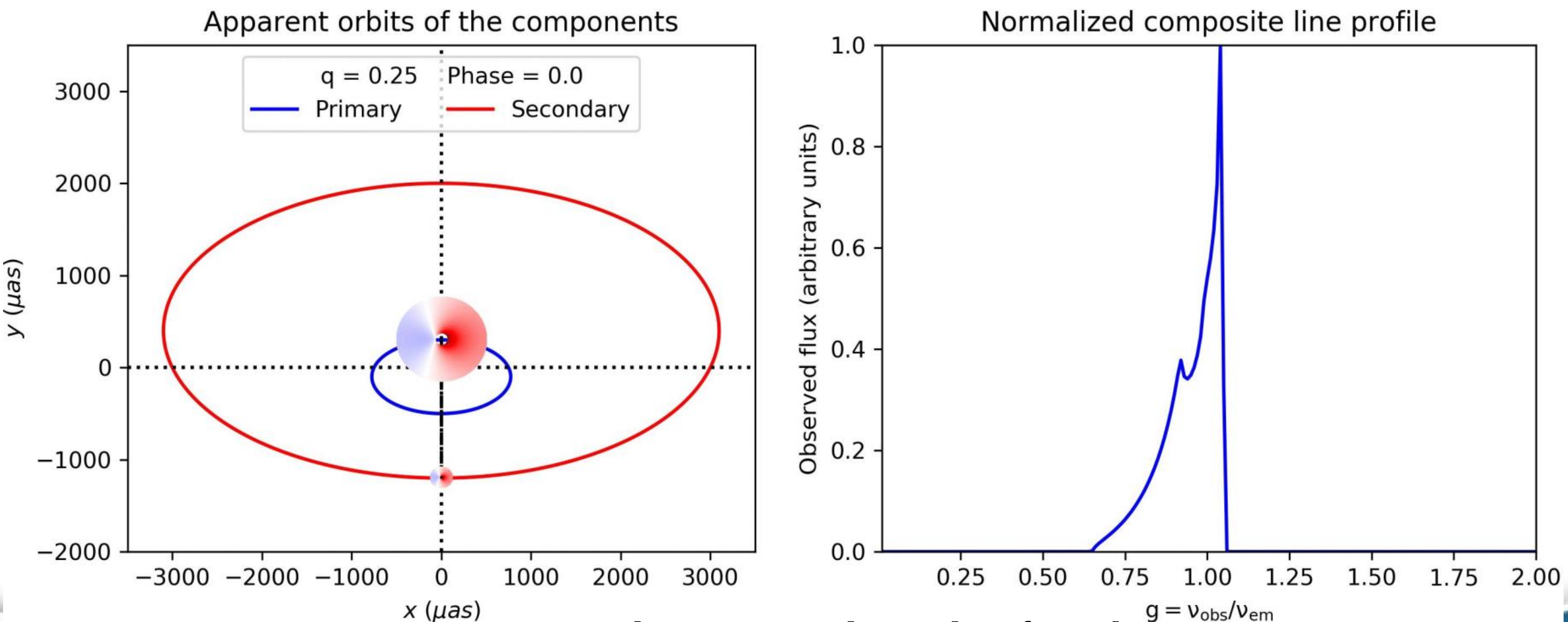
Case 7: SMBHB during different phases of orbit 1, for disk 2 around primary, disk 1 around secondary and for $q = 0.5$ (left), as well as the corresponding composite Fe Kα line profiles (right)



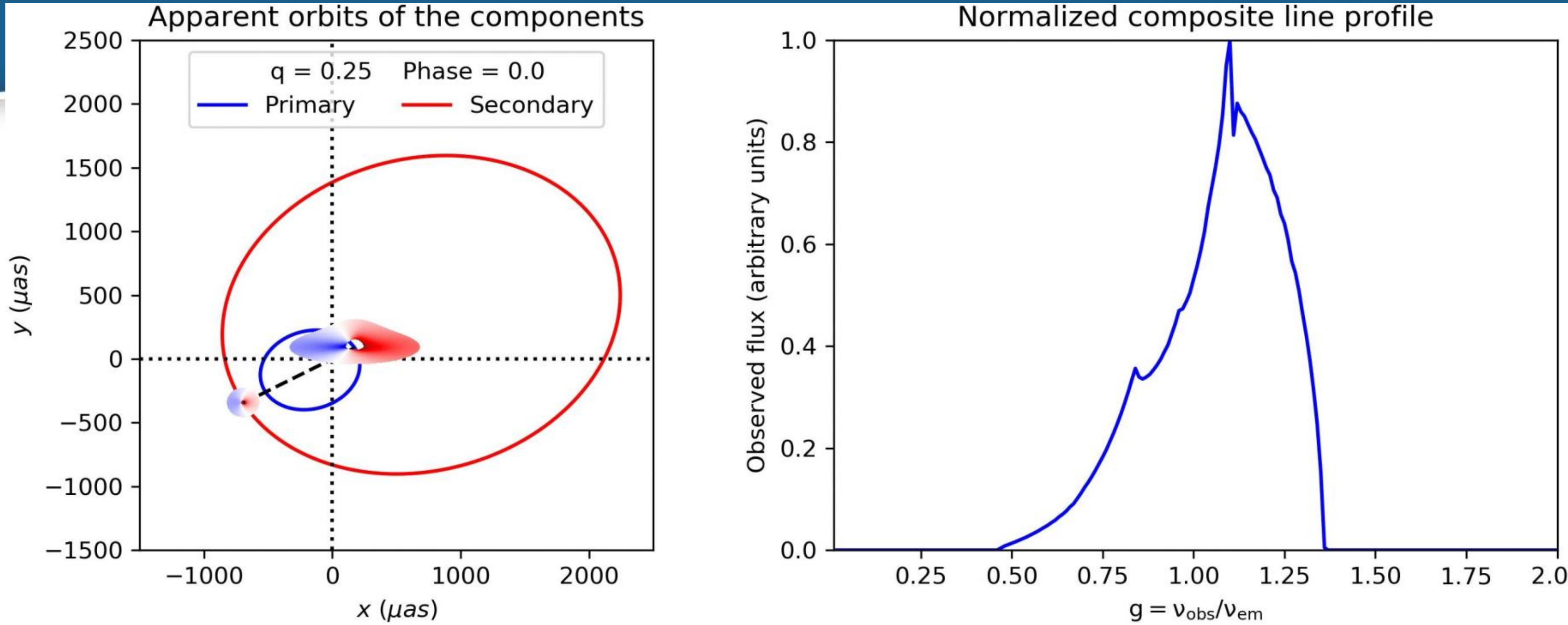
Case 8: The same as above, but for orbit 2



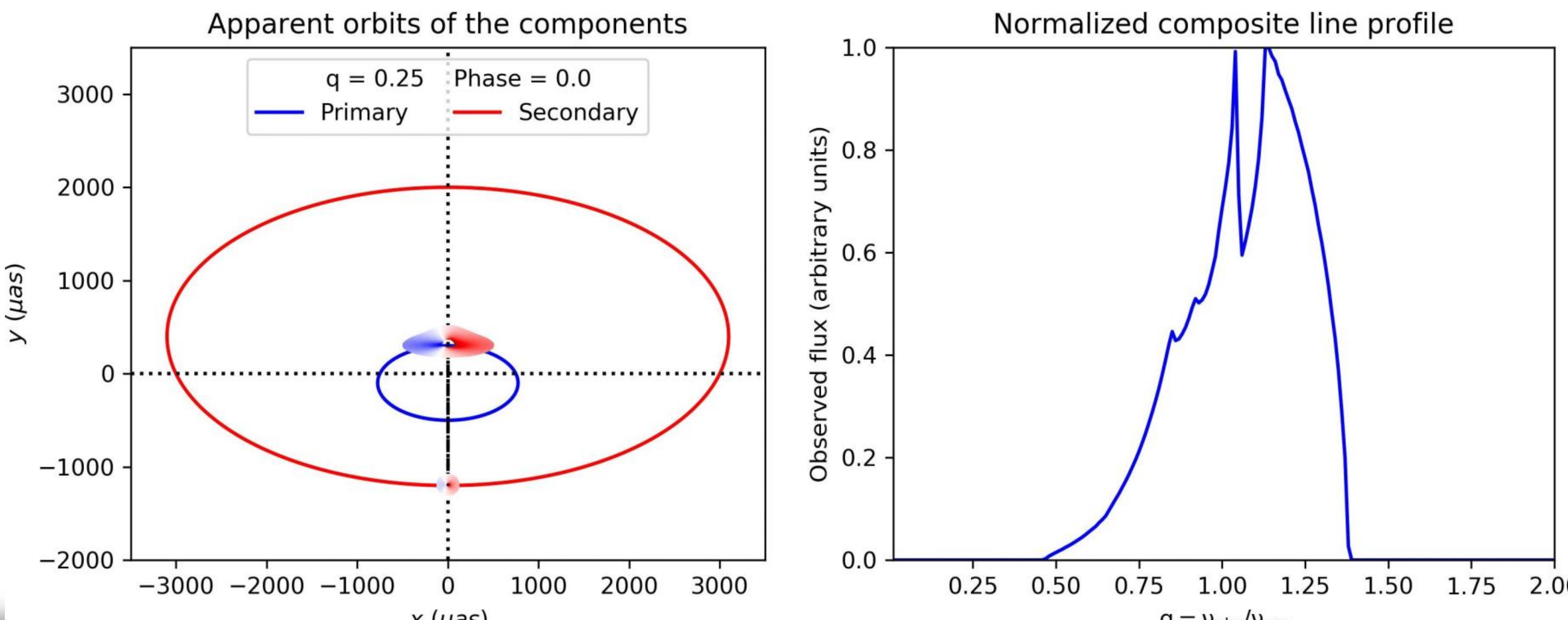
Case 9: SMBHB during different phases of orbit 1, for disk 1 around both primary and secondary and for $q = 0.25$ (left), as well as the corresponding composite Fe Kα line profiles (right)



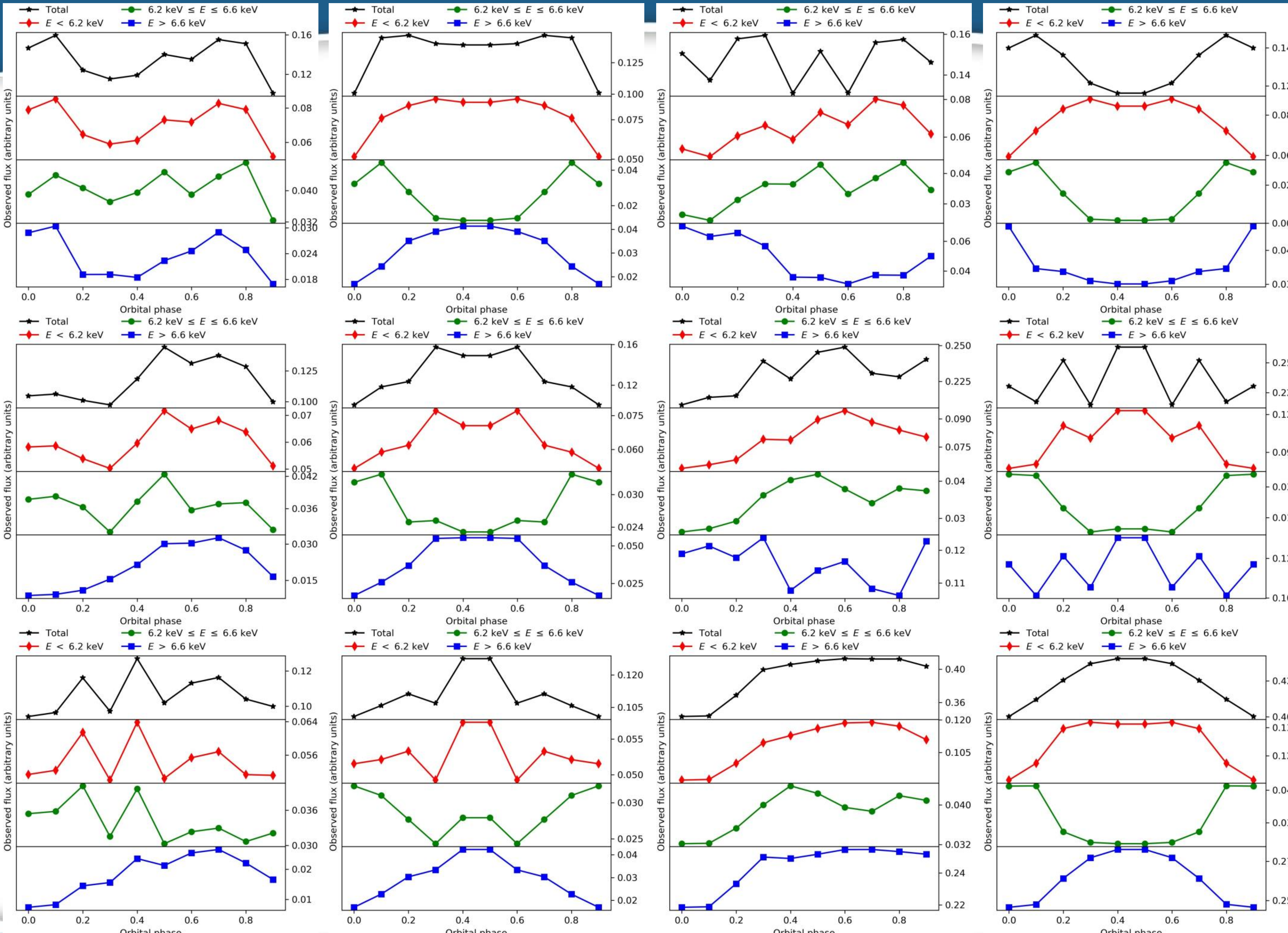
Case 10: The same as above, but for orbit 2



Case 11: SMBHB during different phases of orbit 1, for disk 2 around primary, disk 1 around secondary and for $q = 0.25$ (left), as well as the corresponding composite Fe Kα line profiles (right)

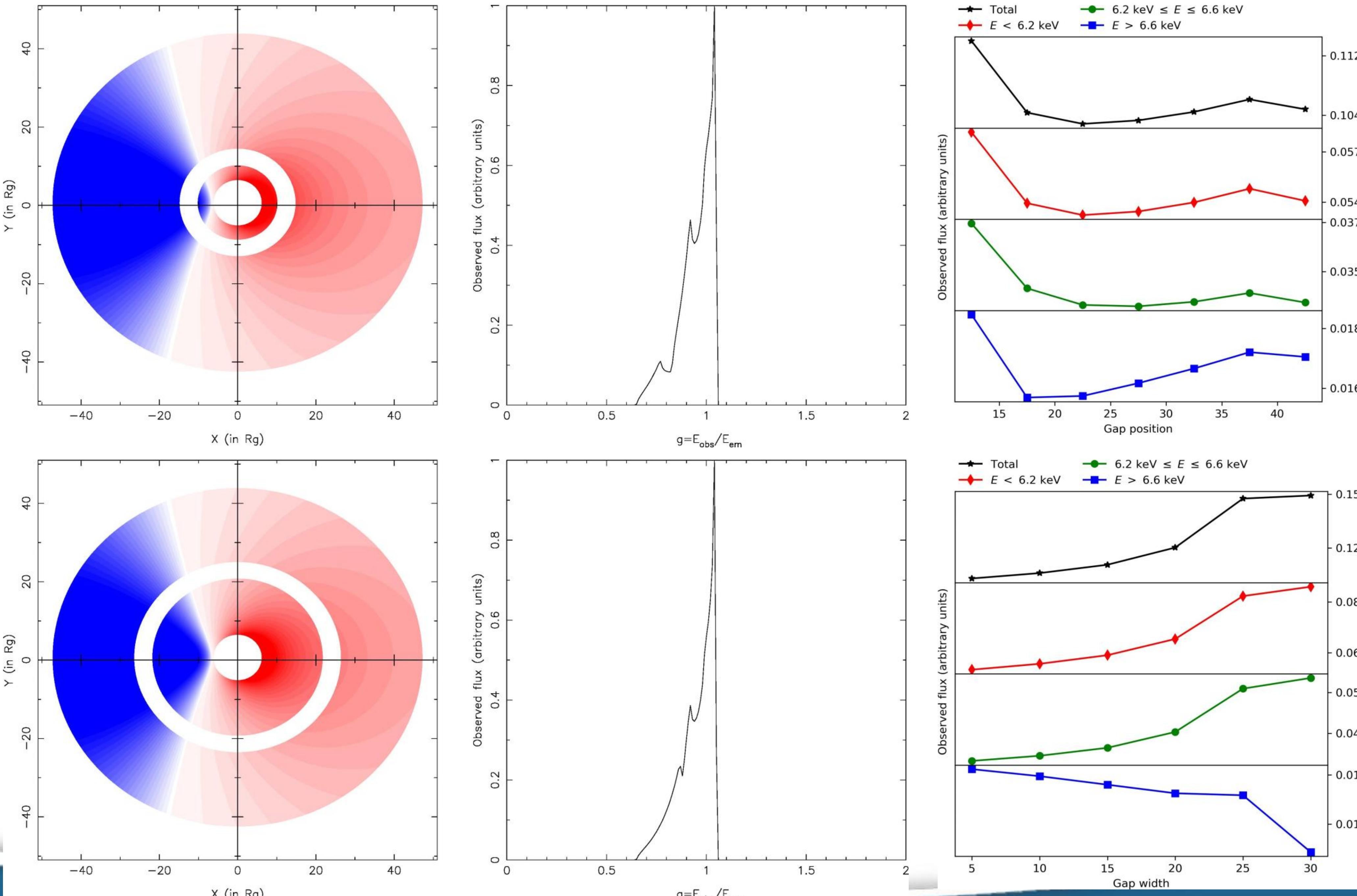


Case 12: The same as above, but for orbit 2

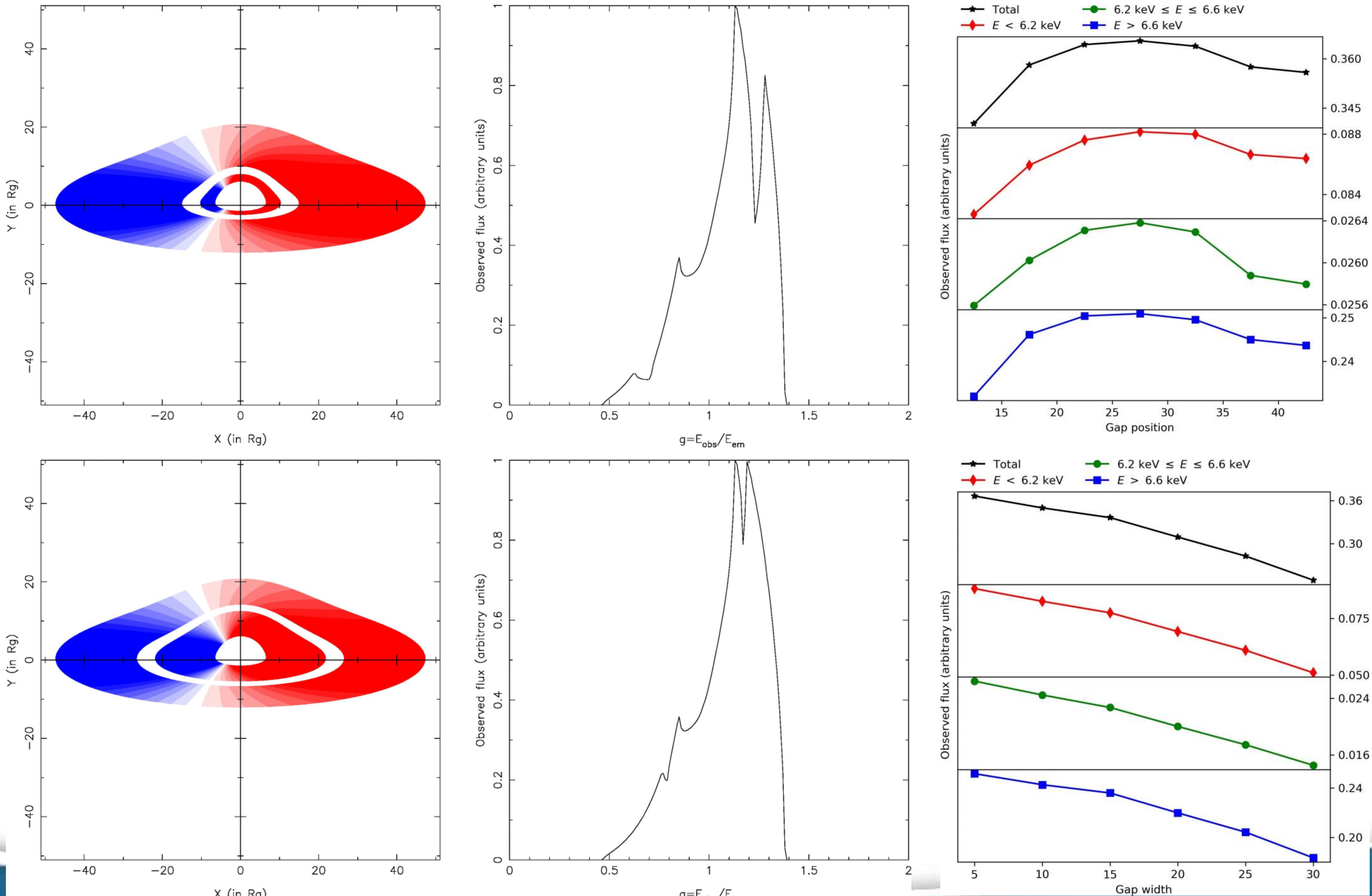


Variability of the flux in different parts of the Fe Kα line for the cases 1-12, respectively

SMBHB model 2: empty gap in the disk 1

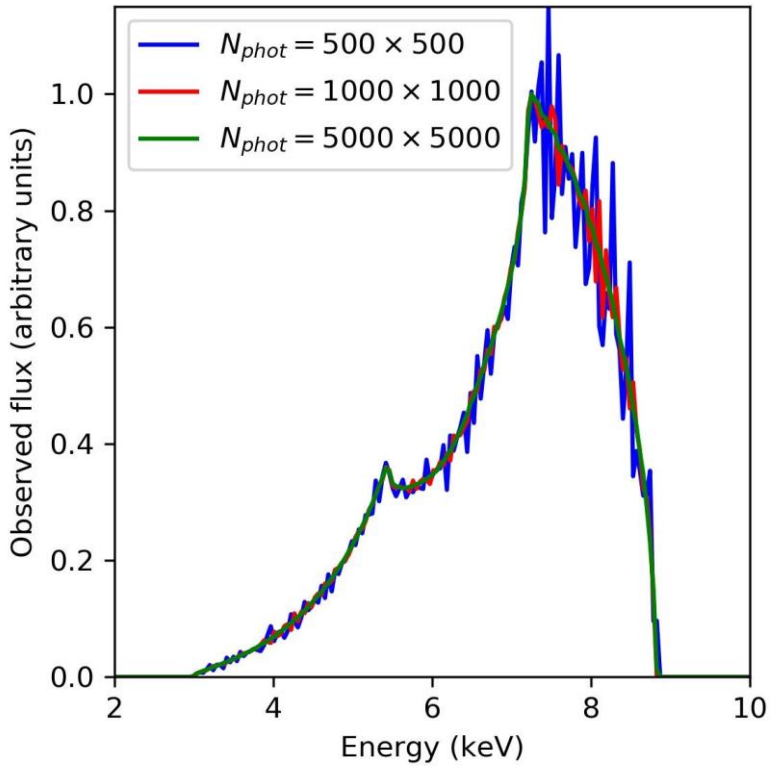


SMBHB model 2: empty gap in the disk 2



Detectability of SMBHB signatures in the observed Fe Kα lines

- A simulated line was calculated over 200 bins of width: ΔE = 0.064 keV $\Rightarrow$ spectral resolution at 6.4 keV is $E/\Delta E$ = 100
- $E/\Delta E$ of modern X-ray telescopes: *XMM-Newton*: ~20 − 50, *Suzaku*: ~600 at 6 keV, *Chandra*: ~100−1000 in 0.1−10 keV range
- In the ray-tracing simulations signal-to-noise ratio depends on the number of photons emitted from a disk (here 5000 □ 5000)
- Large number of photons in our simulations provides much higher S/N ratio than in the current observations by *XMM-Newton* and *Chandra* (although $E/\Delta E$ is close to theirs) □ difficult detection of SMBHB signatures in the observed line profiles
- Future detection by *ATHENA* (*Advanced Telescope for High ENergy Astrophysics*) with high signal-to-noise and high spectral resolution instruments ($E/\Delta E$ ~2800 in 0.2–12 keV range)



Influence of number of photons on the simulated line profiles (see e.g. Milošević, Pursiainen, Jovanović, Popović, 2018. IJMPA, 33, 1845016)

Conclusions

1. We simulated the Fe Kα line profiles emitted from two models of SMBHBs:
   i. both primary and secondary SMBHs are surrounded by an accretion disk and they are orbiting around their center of mass
   ii. the secondary SMBH clears an empty gap (or cavity) in the disk around primary

The obtained results of these simulations showed that:

2. Both models leave detectable ripples in the emitted Fe Kα line profiles
3. In the first model, such ripples in the composite line profiles are caused by Doppler shifts due to orbital motion, and depend on:
   - orbital phase of SMBHB (time) and cause the periodical variability of the line shape
   - mass ratio between the secondary and primary SMBHs
   - parameters of the accretion disks (e.g. inclination) around both primary and secondary
   - Keplerian orbital elements, which could potentially enable reconstruction of the observed radial velocity curves and their fitting with Keplerian orbits
1. In the second model, these ripples do not significantly change in time, but instead:
   - they depend on the parameters of the disk around the primary (inclination and emissivity)
   - their amplitudes strongly depend on the width and distance of the empty gap from the central SMBH, and hence they could be used for constraining the mass ratios and separations between the components in this type of SMBHBs
2. Spectral resolutions and, especially signal-to-noise ratios, of modern X-ray detectors are not sufficient to study in details such signatures of SMBHBs, but this will be possible with the next generation of X-ray observatories (such as *ATHENA*)

Thank you for attention!