The shape of $Fe\ K\alpha$ line emitted from relativistic accretion disc around AGN black holes

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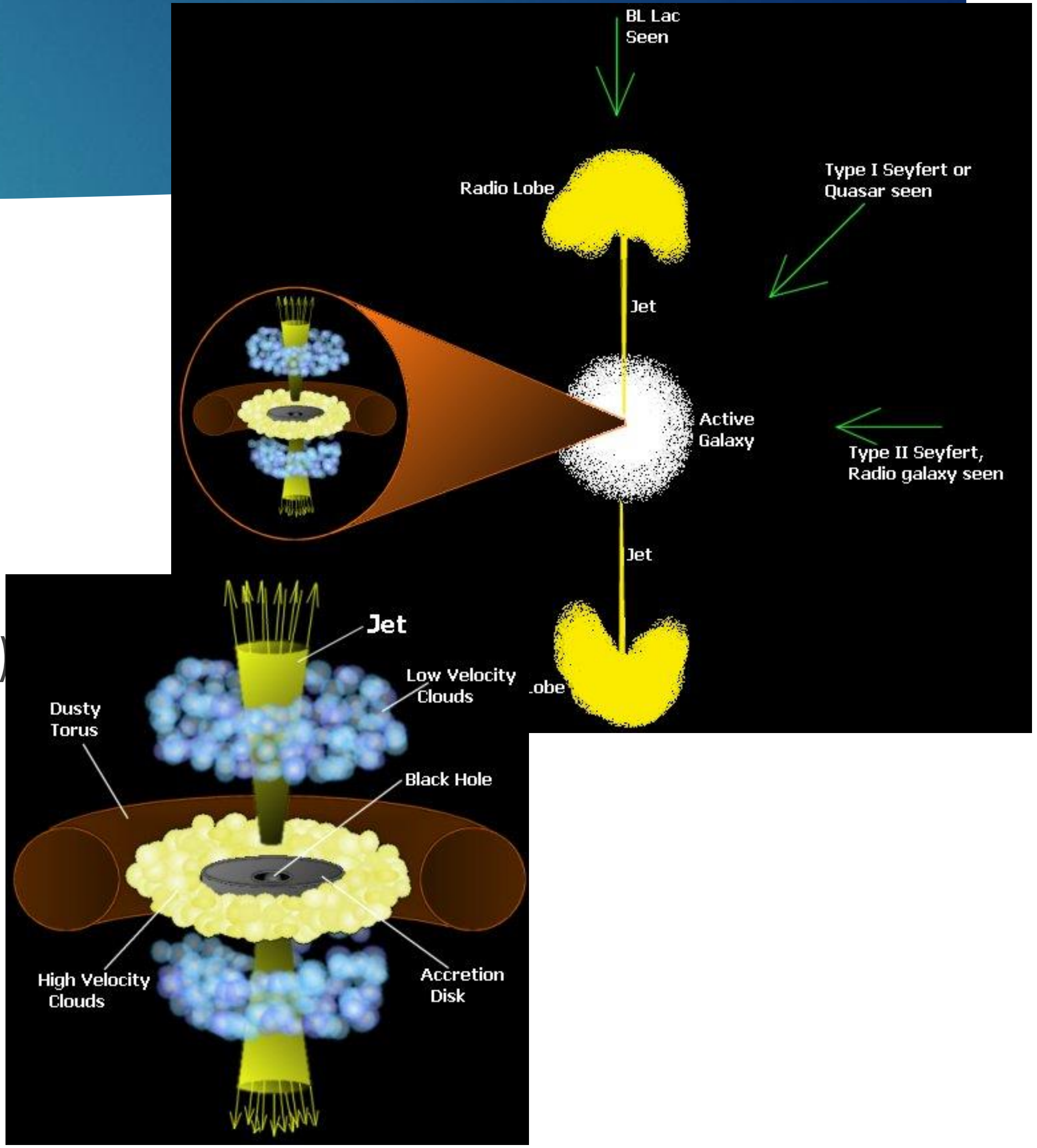
Motivation

- $Fe\ K\alpha$ line was discovered by *Tanaka et al.* (1995) in Seyfert 1 galaxy MCG-6-30-15
- After its discovery it was observed in a number of active galactic nuclei (AGN); early results from ASCA – the broad lines could be resonably common in type 1 AGN (~75% of sample, *Nandra et al.* (1997))
- The broad and asymmetric profile of this line with narrow bright "blue" and wide faint "red" peak is most commonly attributed to the relativistic effects due to a very fast rotation of the emitting material in the innermost regions of the accretion disk
- **Recent studies** – only about a half of the type 1 AGN at low redshifts have relativisticly broadened lines
- We discuss several phenomena which can induce line shifts, and thus cause the variability of the profile using a code based on ray-tracing method in the Kerr metric

AGN and SMBH

- Active Galactic Nuclei (AGN) – one of the most energetic sources of radiation
- Radiate in all spectral bands from radio to γ-rays; luminosity $\sim 10^8 - 10^{14} L_\odot$
- Power – accretion of matter from the host galaxy towards a central Supermassive Black Hole (SMBH)
- The SMBH is surrounded by a geometrically thin, optically thick accretion disc which at larger distances expands into a torus.

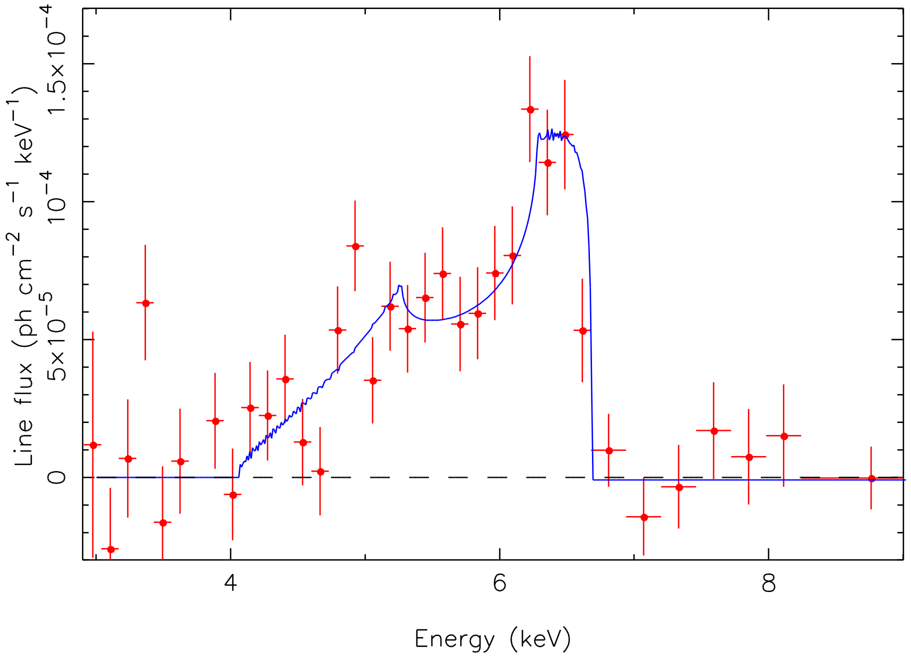


Classification of Black Holes (BH)

- classification according to the metric:
  - Schwarzschild (non-rotating and uncharged)
  - **Kerr (rotating and uncharged)**
  - Reissner–Nordström (non-rotating and charged)
  - Kerr–Newman (rotating and charged)
- classification according to their masses:
  - Mini, micro or quantum mechanical: $M_{BH} \ll M_{\odot}$(primordial black holes in the early universe)
  - stellar-mass: $M_{BH} < 10^2 M_{\odot}$ (in X-ray binary systems)
  - intermediate-mass: $M_{BH} \sim 10^2 - 10^5\ M_{\odot}$ (in the centers of globular clusters)
  - **supermassive**: $M_{BH} \sim 10^5 - 10^{10}\ M_{\odot}$ (in the centers of all galaxies, including ours)

AGN and SMBH

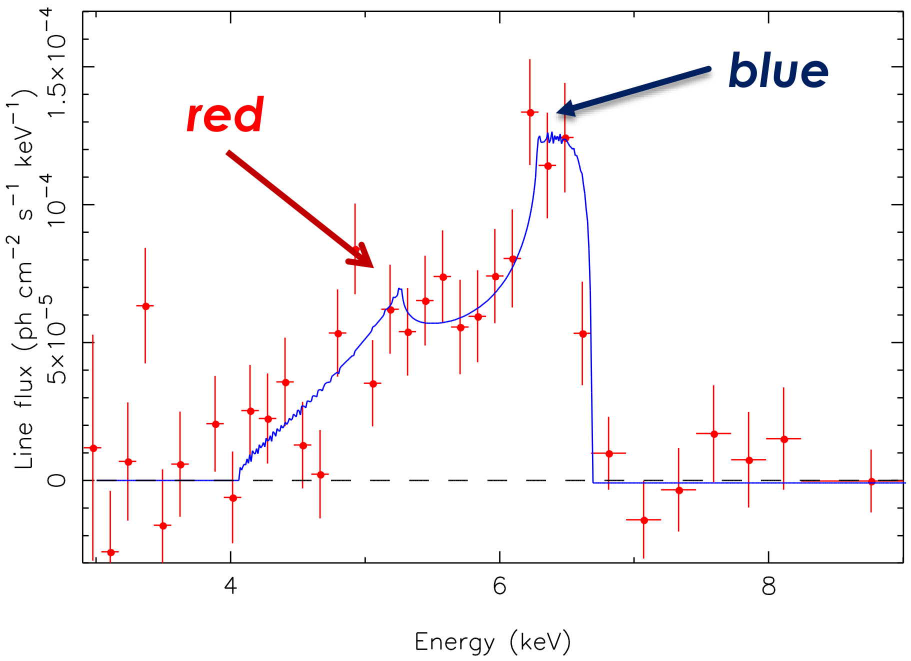
- The plasma in the accretion disc loses angular momentum due to viscosity of the plasma forcing the matter to fall inwards.
- The release of gravitational potential energy heats up the plasma as it keeps flowing towards the black hole, reaching temperatures of millions of degrees in the inner parts of the disc.
- At these temperatures matter mostly radiates in the X-ray band.
- Unlike in the UV and optical spectra of AGN, in the X-ray band there are only a few strong emission lines.
- Due to the sufficiently high iron abundance in the disc iron $K\alpha$ (6.4-6.9 keV, depending on the ionization state) is the strongest of them.



Tanaka et al, 1995, *Nature*, **375**, 659

AGN and SMBH

- The narrow $K\alpha$ line from neutral iron (at 6.4 keV) is present in the spectra of majority of AGN, most likely originating from more distant colder material in the outer parts of the disc or the torus for instance
- Same line originating from more inner parts of the accretion disc, is also very common in the X-ray spectra of AGN
- Broad emission spectral line at 6.4 keV; Dopler motion and the relativistic effects due to presence of massive compact object
- Asymmetric profile with narrow bright **blue** peak and wide faint **red** peak

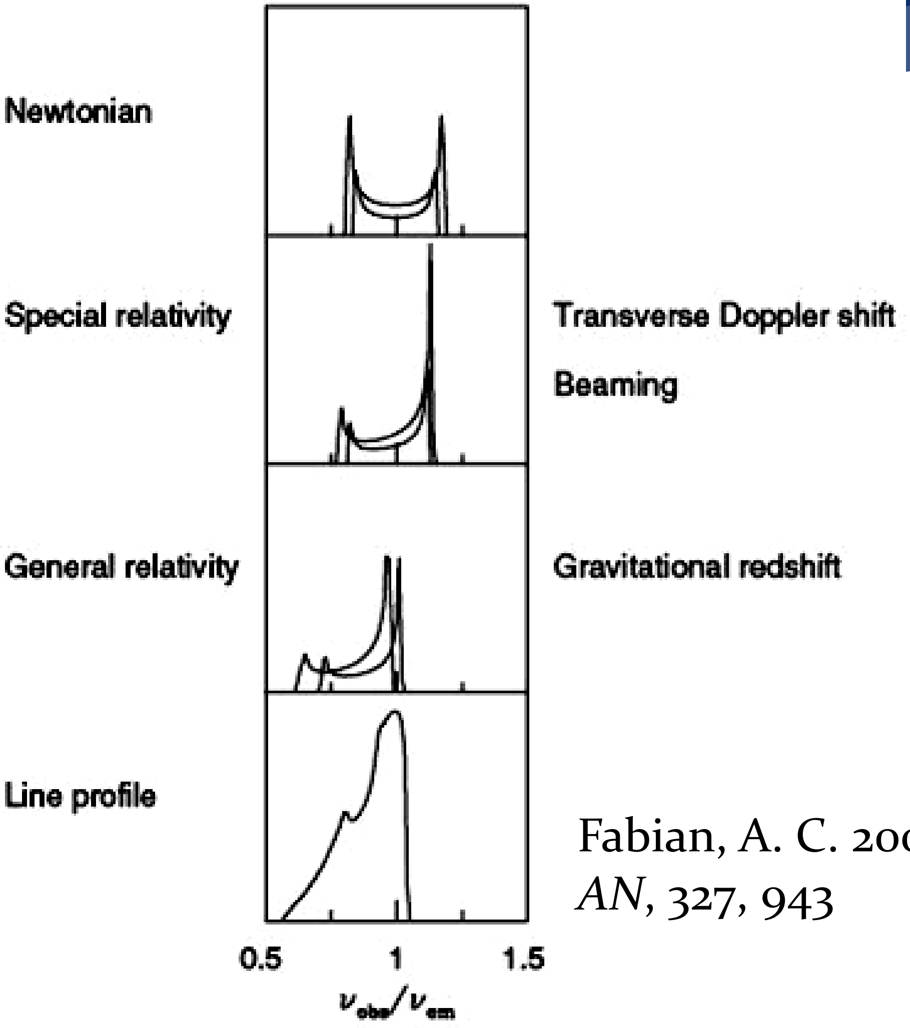


Tanaka et al, 1995, *Nature*, **375**, 659

The $Fe\ K\alpha$ line

- Classical Doppler shift: symmetric, double-peaked profile
- Special relativistic transverse Doppler shift and relativistic beaming: enhance blue peak relative to red peak
- General relativistic gravitational redshift: smearing blue emission into red:

$$1 + z = \frac{1}{\sqrt{1 - \frac{2GM}{rc^2}}},$$



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

Ray-tracing in Kerr metric

- In units where $G = c = 1$:

$$ds^2 = -\left(1 - \frac{2Mr}{\Sigma}\right) dt^2 - \frac{4Mar}{\Sigma} \sin^2\theta dt d\phi + \frac{A}{\Sigma} \sin^2\theta d\phi^2 + \frac{\Sigma}{\Delta} dr^2 + \Sigma d\theta^2,$$

$$\Sigma = r^2 + a^2 \cos^2\theta, \quad \Delta = r^2 + a^2 - 2Mr, \quad A = (r^2 + a^2)^2 - a^2 \Delta \sin^2\theta$$

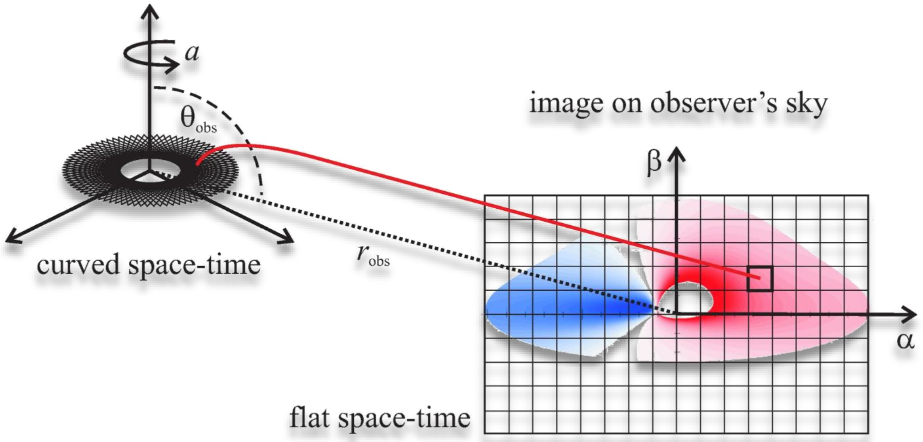
- horizon of BH: $\Delta = 0 \Rightarrow r_h = M + \sqrt{M^2 - a^2}$
- radius of marginally stable orbit:

$$r^2 - 6Mr \mp 8a\sqrt{Mr} - 3a^2 = 0 \Rightarrow R_{ms} = \begin{cases} 6M, & a = 0 \\ M, & a = M \end{cases}$$

- Two approaches:
  1. integrating the null geodesic equations starting from a given initial position in the disk to the observer at infinity
  2. **tracing rays** following the trajectories from the sky plane to the disk (only those photon trajectories that reach observer's sky plane are considered

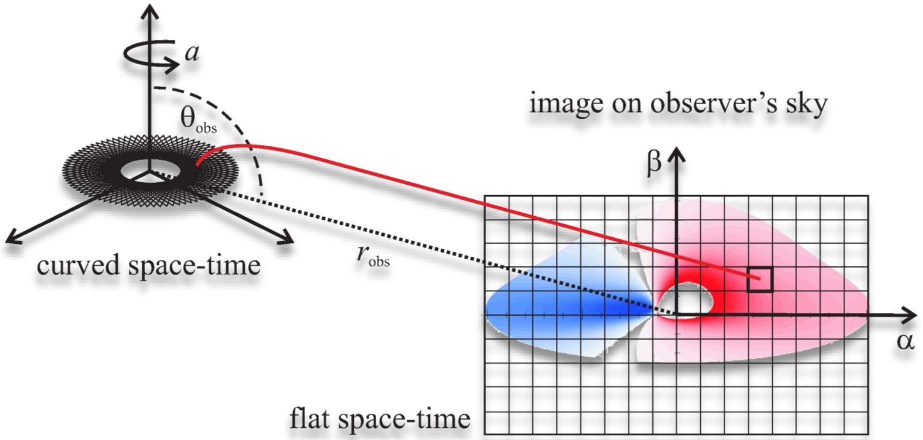
Simulation

- The line emission from the accretion disc around a SMBH can be analyzed with numerical simulations based on the ray-tracing method in the Kerr metric
- Only the photon trajectories that reach the sky plane of the observer
- The image of the disk on the observer's sky is divided into small pixels
- Photon trajectories for each pixel can be traced backward…



Simulation

- Photon trajectories for each pixel can be traced backward
  - starting from the observer following the geodesics in the Kerr space-time
  - The geodesics will cross the plane of the disc at individual points
  - For each point the flux density of the disc radiation and the redshift/blueshift can be calculated
- The simulated line profile can then be calculated based on the disc images by taking into account the intensities and received photon energies of all pixels



Ray-tracing method

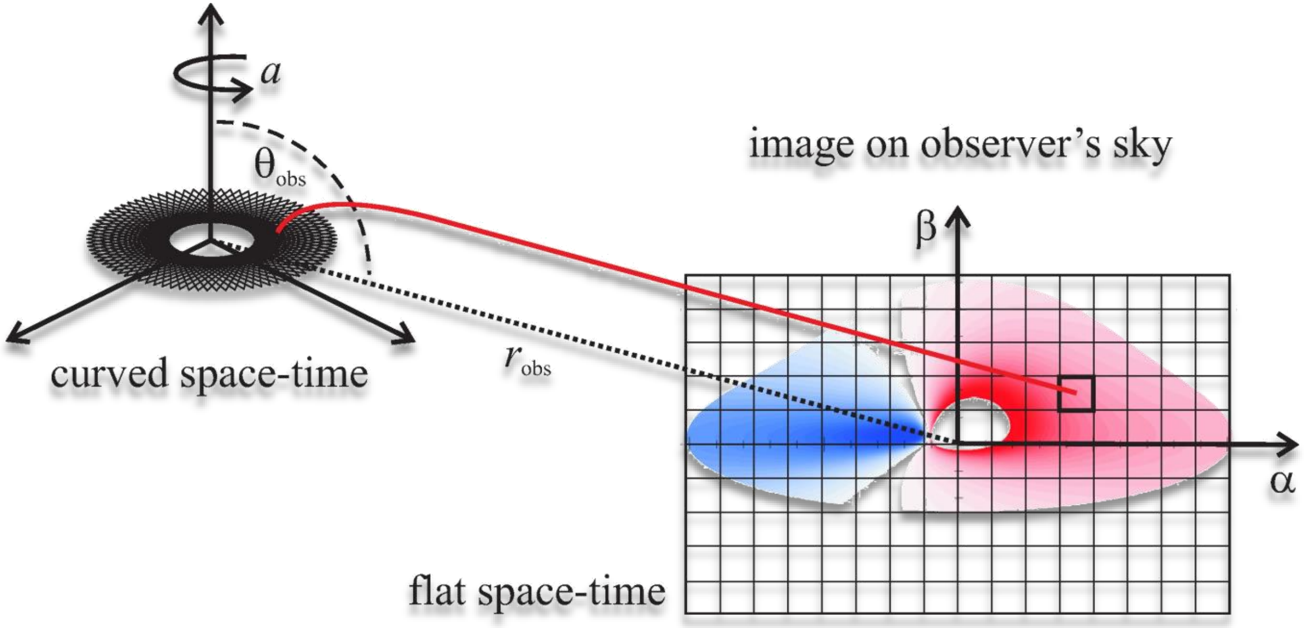
$$\alpha = -\frac{\lambda}{\sin\theta_{\rm obs}},$$

$$\beta = \pm\left[q^2 + (a\cos\theta_{\rm obs})^2 - (\lambda\cot\theta_{\rm obs})^2\right]^{1/2}$$

$$\pm\int_{r_{\rm em}}^{\infty}\frac{dr}{\sqrt{R(r,\lambda,q)}} = \pm\int_{\theta_{\rm em}}^{\theta_{\rm obs}}\frac{d\theta}{\sqrt{\Theta(\theta,\lambda,q)}}$$

$$R(r,\lambda,q) = \{(r^2+a^2-a\lambda)^2 - \Delta[(\lambda-a)^2+q^2]\}$$

$$\Theta(\theta,\lambda,q) = \left[q^2 + (a\cos\theta)^2 - (\lambda\cot\theta)^2\right]$$



- Surface emissivity of the disk:

$$\varepsilon(r) = \varepsilon_0 \cdot r^q$$

- Frequency ratio (energy shift):

$$g = \frac{\nu_{obs}}{\nu_{em}} = \frac{1}{1+z}$$

- Total observed flux:

$$F_{obs}(E_{obs}) = \int_{image} \varepsilon(r)\cdot g^4 \delta(E_{obs} - gE_0)\,d\Xi,$$

Simulation

- All simulated line profiles are done using the ray-tracing method with an approach proposed by A. Čadež et al. (1998).
- About 60000 accretion disks and corresponding iron $K\alpha$ line were simulated.
- Variable parameters:
  - Emissivity index (q), inclination (i), inner radius (R_{in}), outer radius (R_{out}), spin of the BH (a), different number of counts;
  - Each set of parameters was calculated for different counts of photon and different bin size.

A. Čadež, C. Fanton, M. Calvani, New Astron. 3 (1998), pp. 647 - 654.
L. Popović, E.G. Mediavilla, P. Jovanović, J.A. Munoz,, A&A 398 (2003), pp. 975 - 982.
L. Popović, P. Jovanović, E. Mediavilla, A.F. Zakharov, C. Abajas, J.A. Munoz, G. Chartas, ApJ 637 (2006), pp. 620 - 630.
P. Jovanović, New Astron. Rev. 56 (2012), pp. 37 - 48.

Simulation

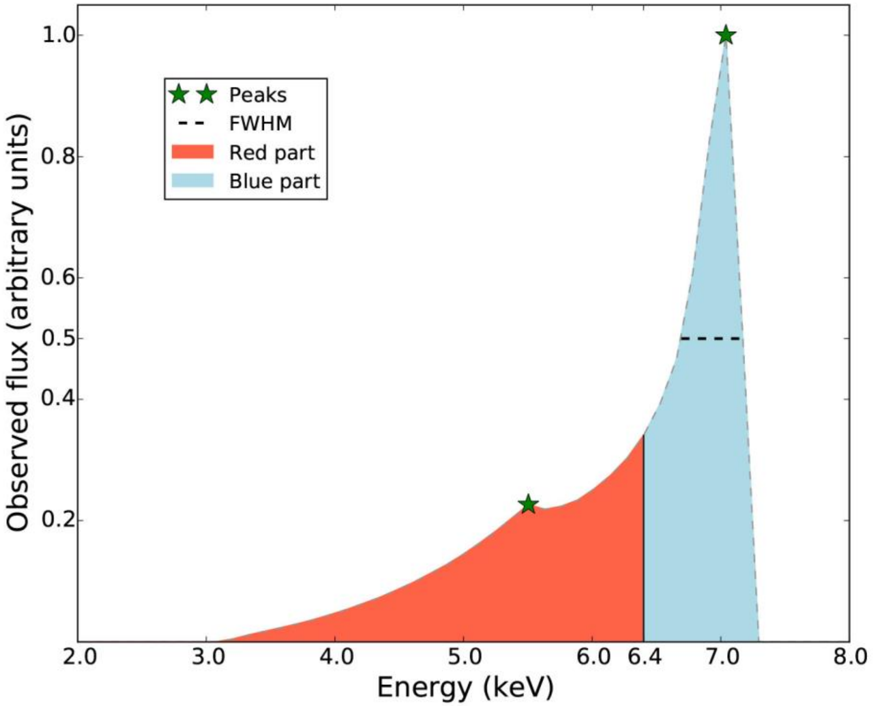
Sample	q	i (°)	$R_{in}(R_g)$	$R_{out}(R_g)$	a	n_{res}	n_{bin}	**No**
1	2.5, 3	5-80 (5)	r_{ms}	10, 20, 30, 50, 70, 100	0.05 - 0.998 (0.1)	5000	50	2304
2	2.5, 3	5-80 (5)	from r_{ms} to $r_{ms} + 10$ (1)	from $R_{in} + 10$ to $R_{in} + 30$ (10)	0.05 - 0.998 (0.1)	5000	50	12672
3	2, 2.5, 3, 4	5-80 (5)	r_ms	10, 20, 30, 50, 70, 100	0.05 - 0.998 (0.1)	1000, 3000, 5000	50, 70, 80, 100	55296

$\boldsymbol{R_g = \frac{GM}{c^2}}$ - gravitational radius

$a = 0.05$ – almost non-rotating BH,
$a = 0.998$ – maximally rotating Kerr BH

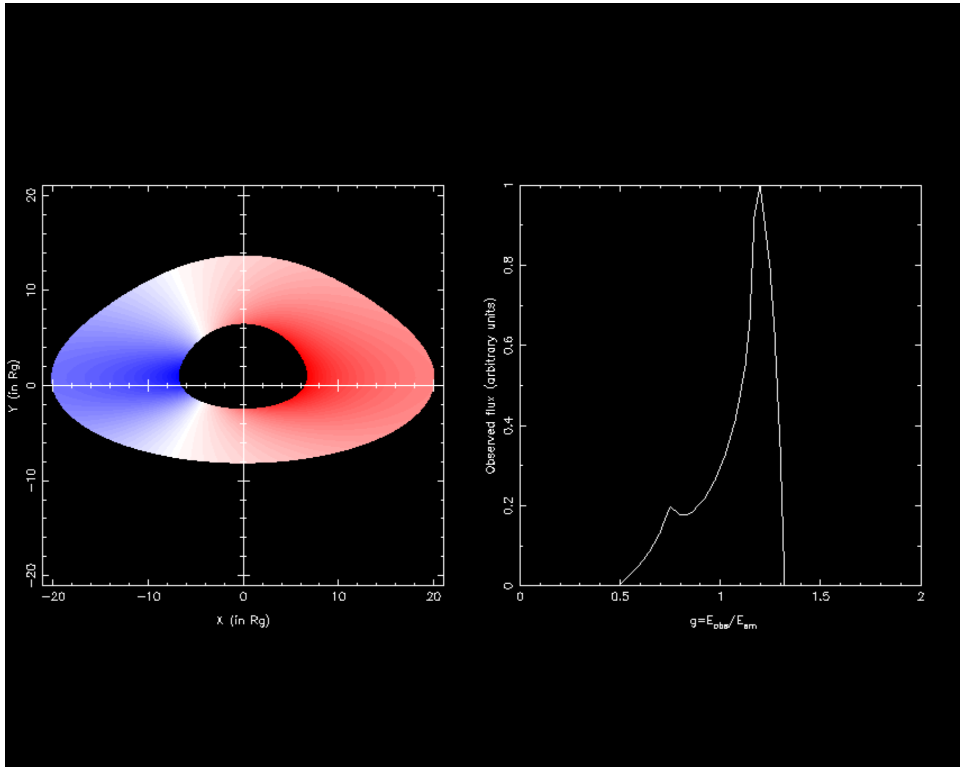
Spin – determinates innermost stable orbit around SMBH, *marginally stable orbit* r_{ms}
For $a = 0.05 \Rightarrow r_{ms} = 5.84R_g$ and $a = 0.998 \Rightarrow r_{ms} = 1.24R_g$

The $Fe\ K\alpha$ line parameters

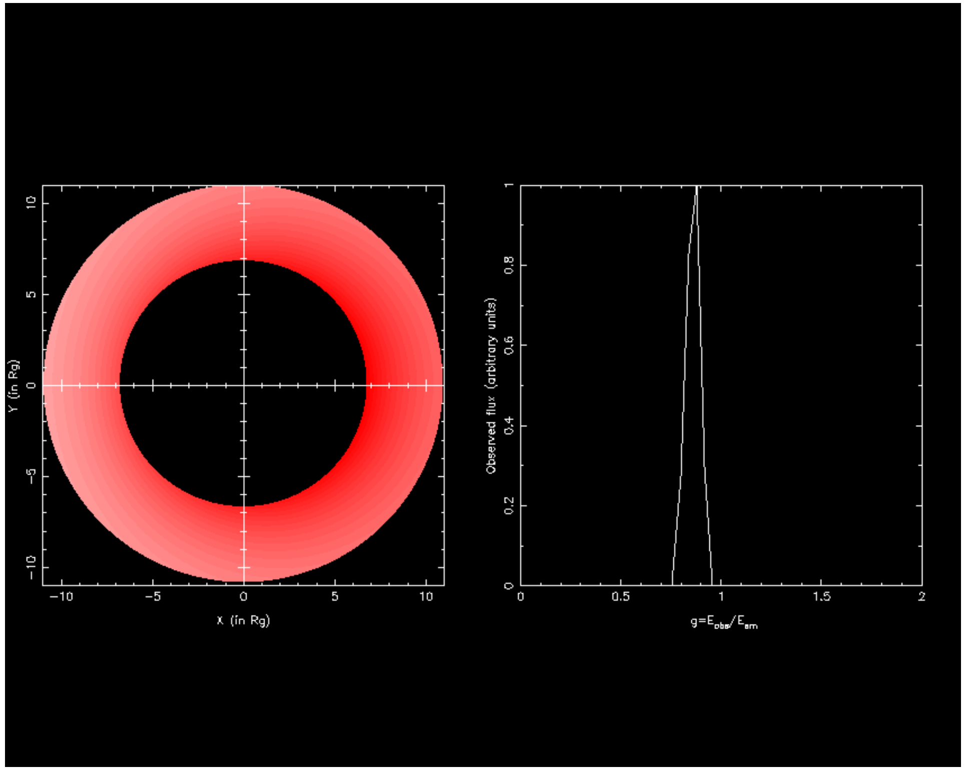


- Asymmetric ratio
  - Dividing the total flux of line above 6.4 keV by the total flux of the line below (blue / red)
- Full width at half maximum (FWHM) – in most cases width of the blue peak

Simulated profiles of $Fe\ K\alpha$ line

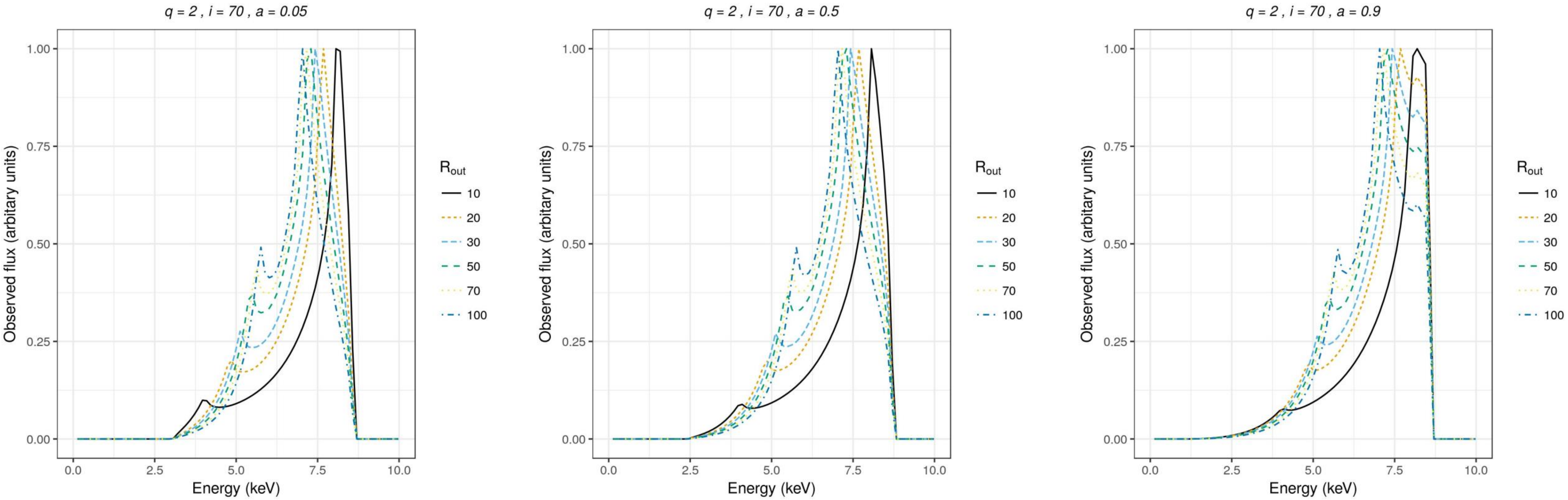


$q = 2.5$, $\mathrm{i} = 65$, $R_{in} = r_{ms}$, $R_{out} = 20$, $a = 0.05$, $n_{res} = 5000$, $n_{bin} = 80$

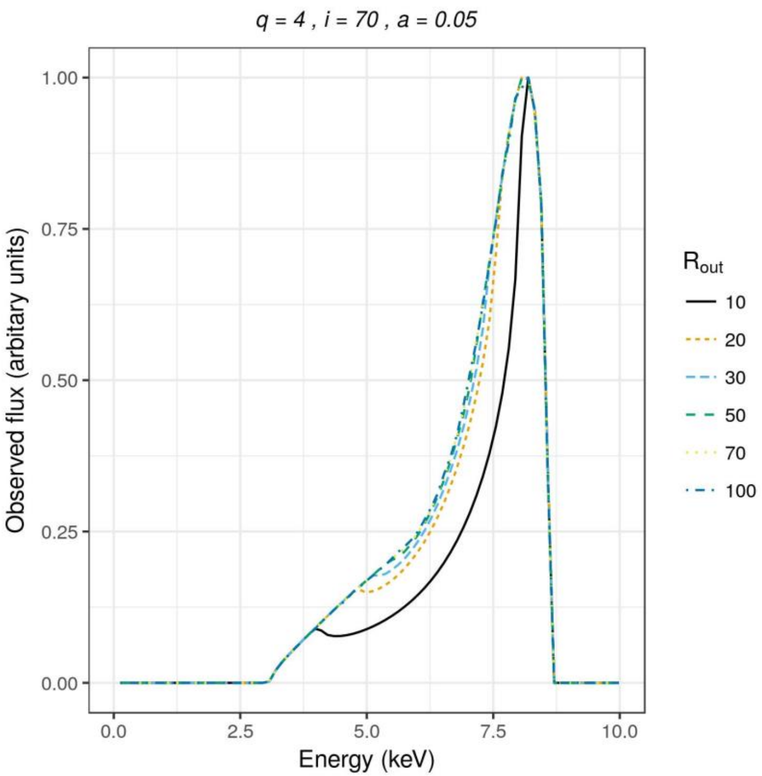


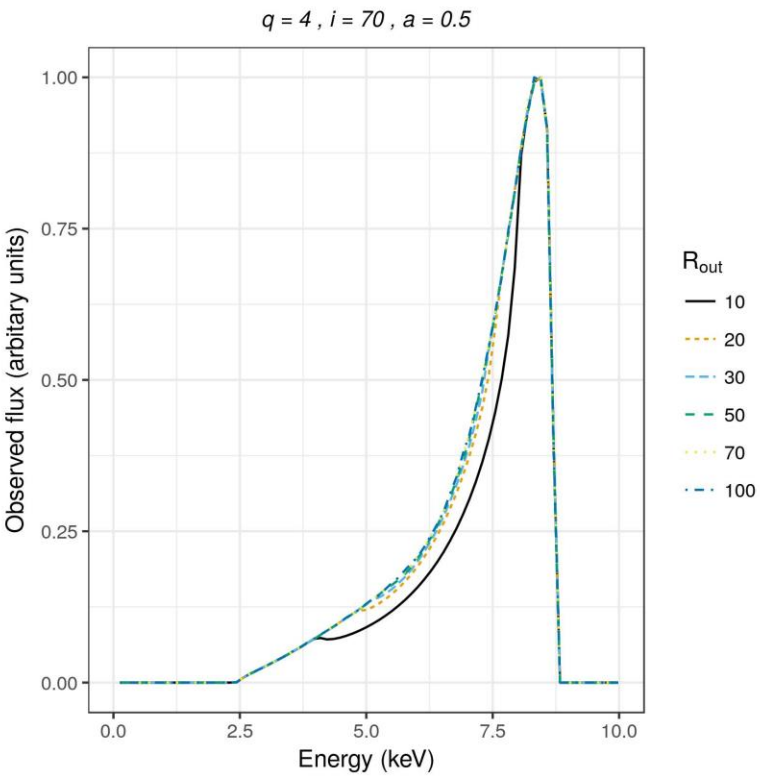
$q = 2$, $\mathrm{i} = 1$, $R_{in} = r_{ms}$, $R_{out} = 10$, $a = 0.05$, $n_{res} = 5000$, $n_{bin} = 80$

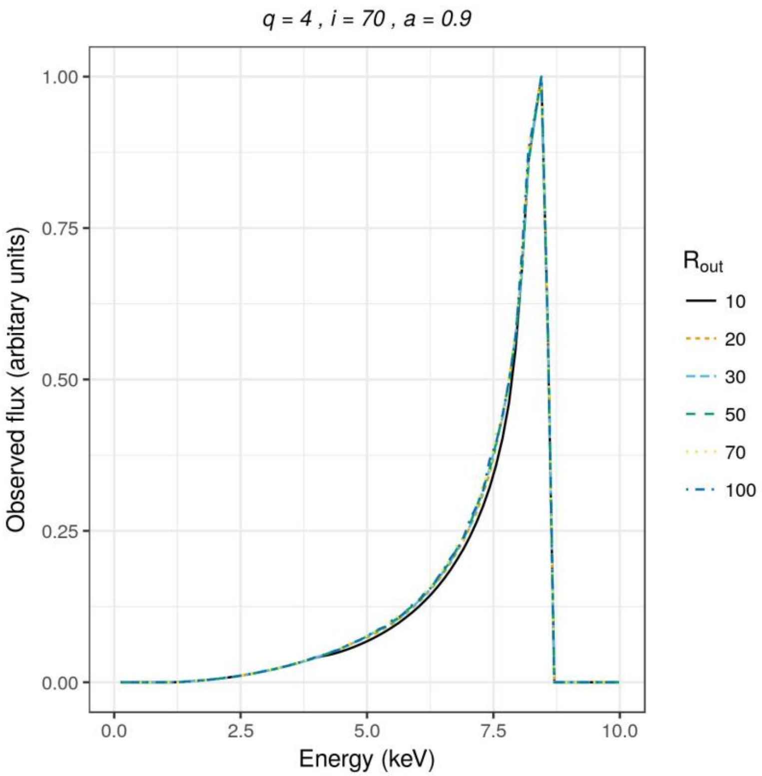
Simulated profiles: effects of spin



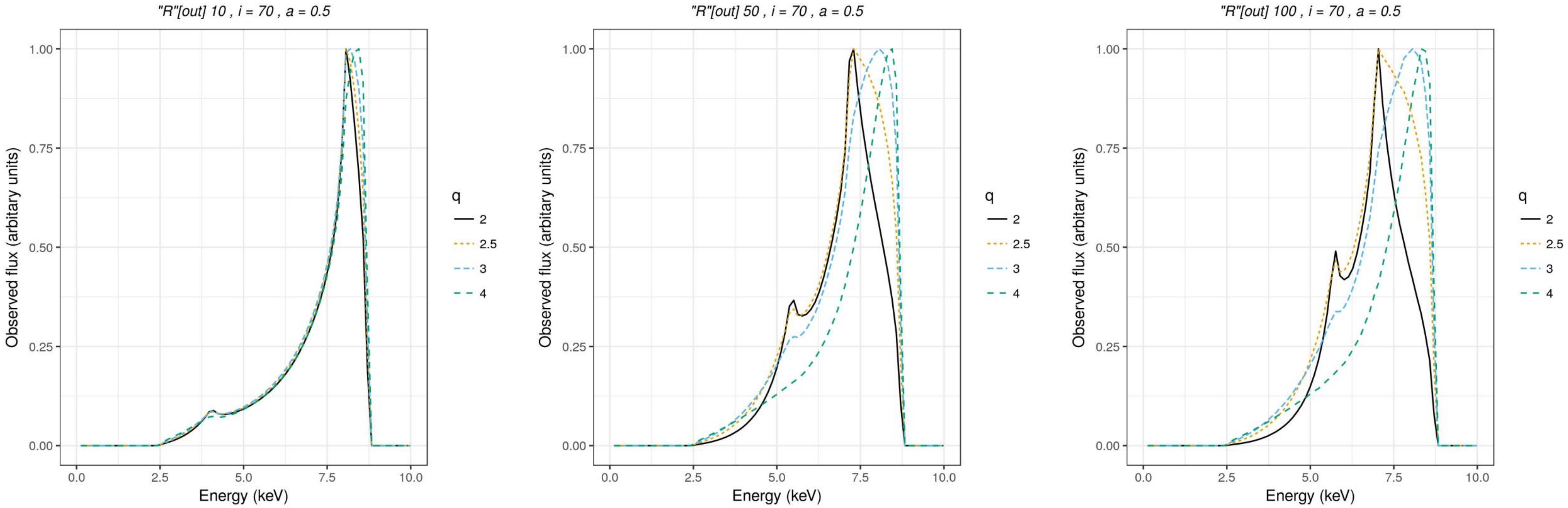
Simulated profiles: effects of spin


q = 4 , i = 70 , a = 0.05

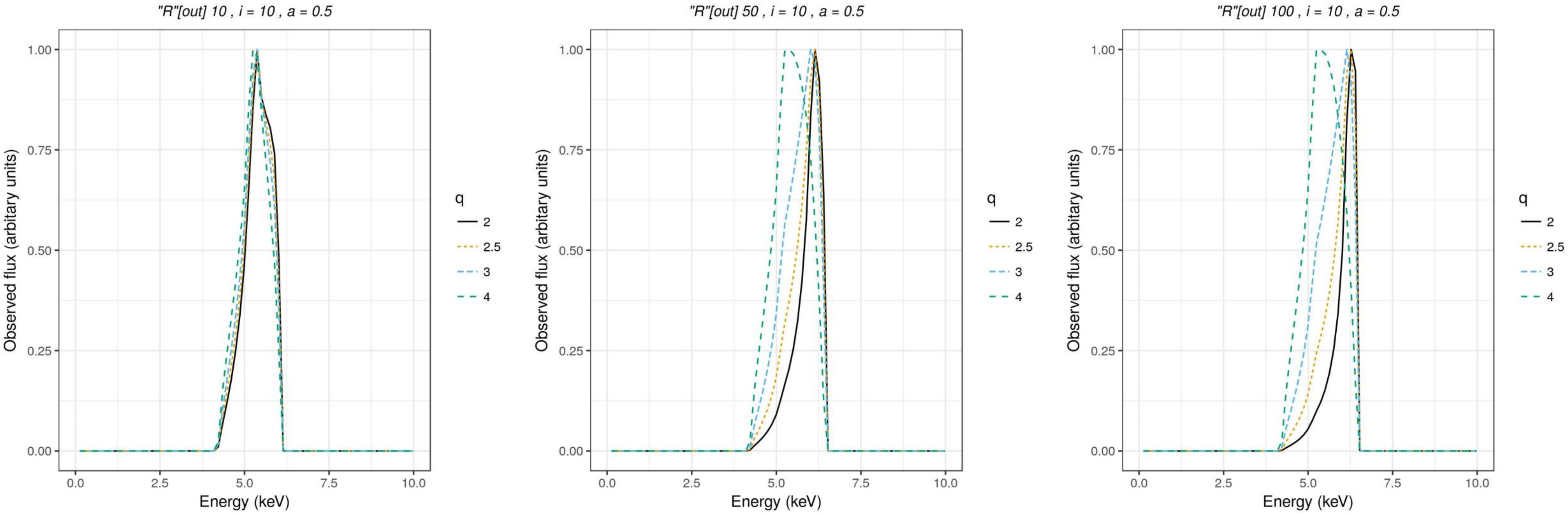

q = 4 , i = 70 , a = 0.5


q = 4 , i = 70 , a = 0.9

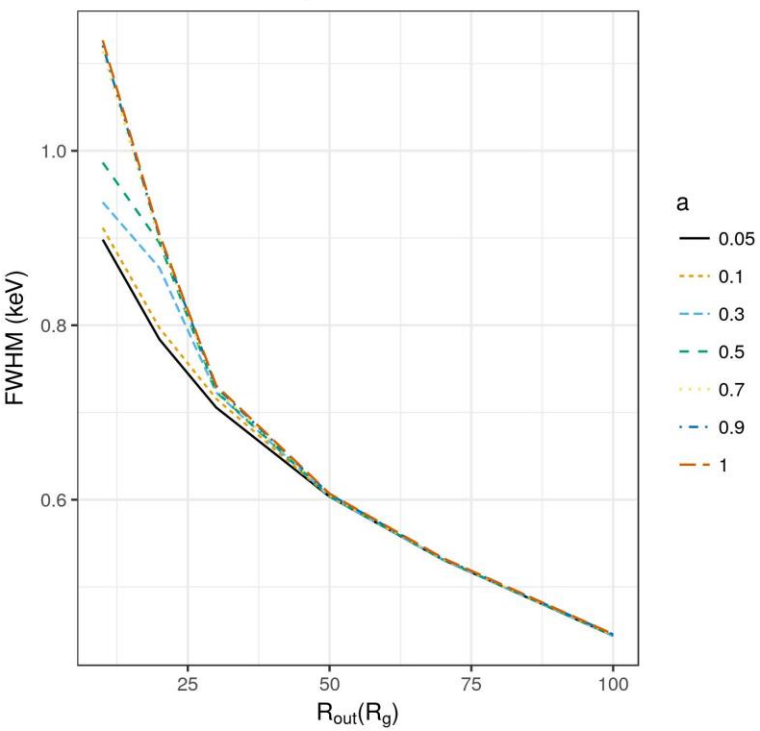
Simulated profiles: effects of R_{out}

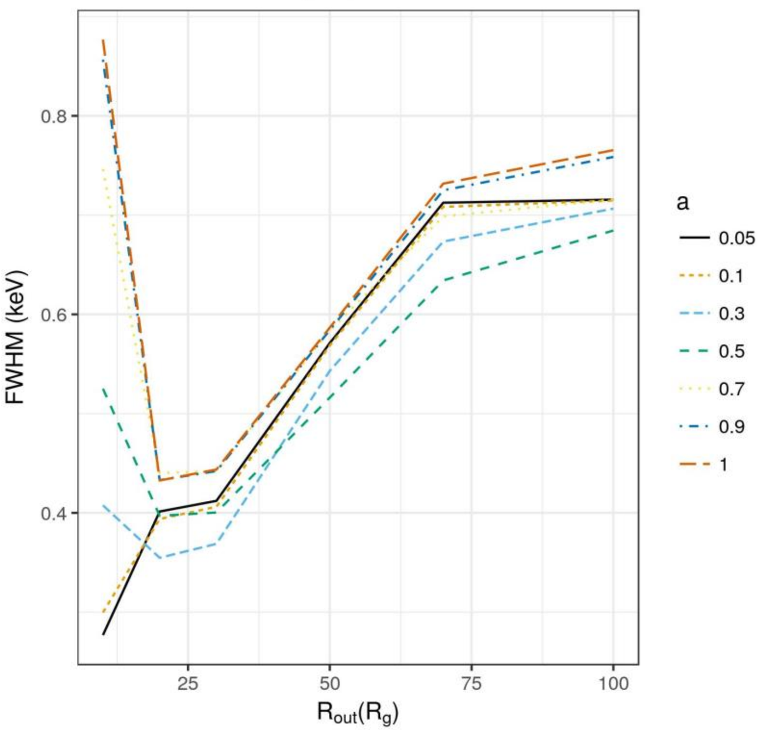


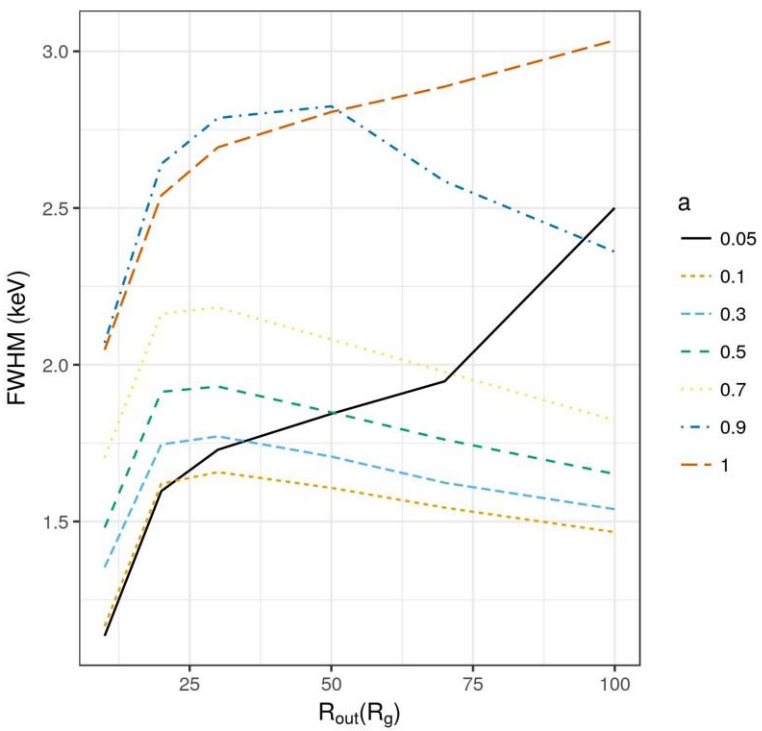
Simulated profiles: effects of R_{out}



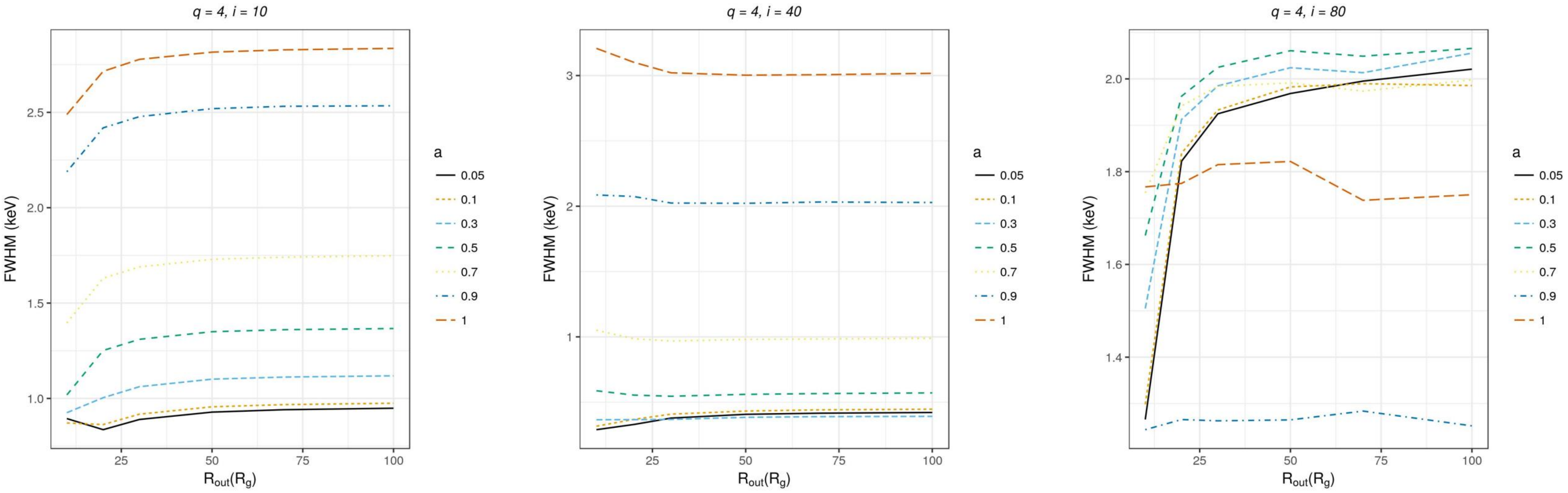
FWHM


q = 2, i = 10

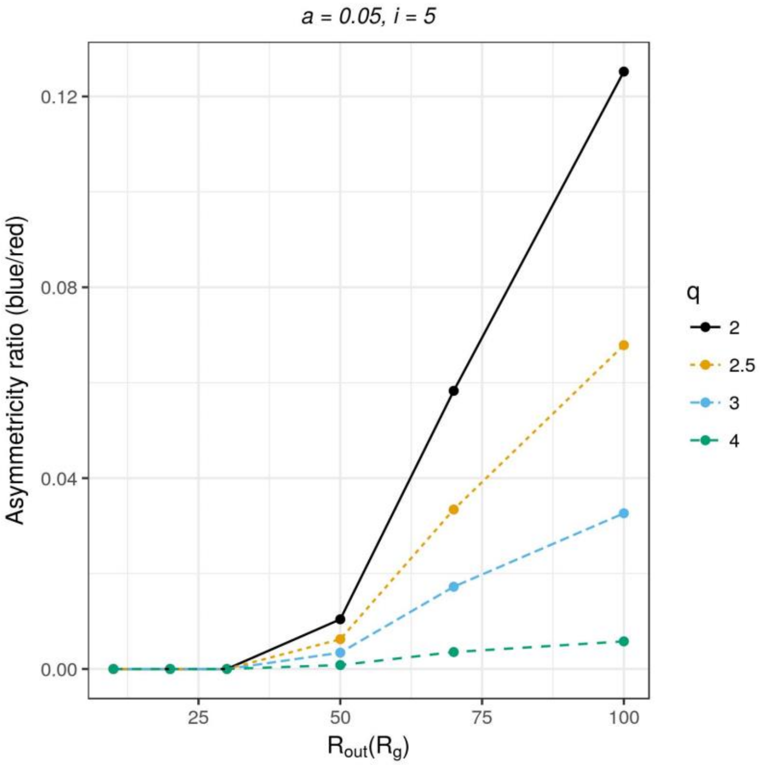

q = 2, i = 40

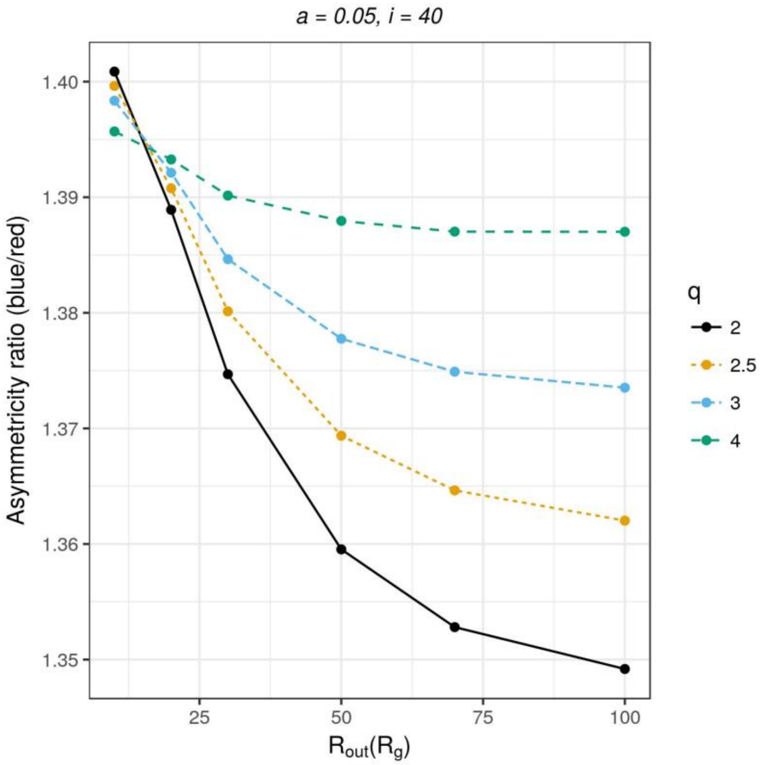

q = 2, i = 80

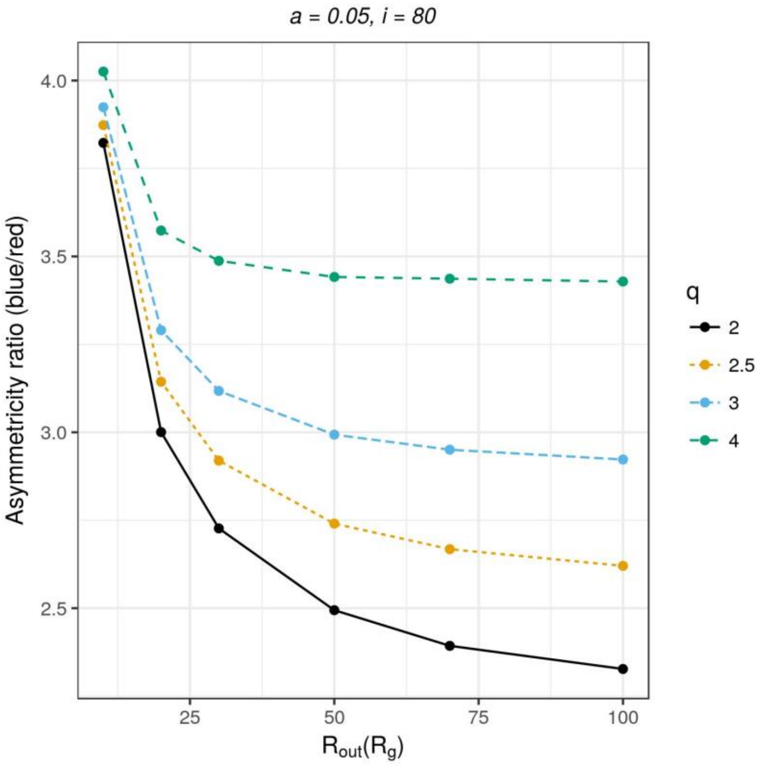
FWHM


q = 4, i = 10
q = 4, i = 40
q = 4, i = 80
FWHM (keV)
2.5
2.0
1.5
1.0
3
2
1
1.8
1.6
1.4
25
50
75
100
R_out(R_g)
a
0.05
0.1
0.3
0.5
0.7
0.9
1

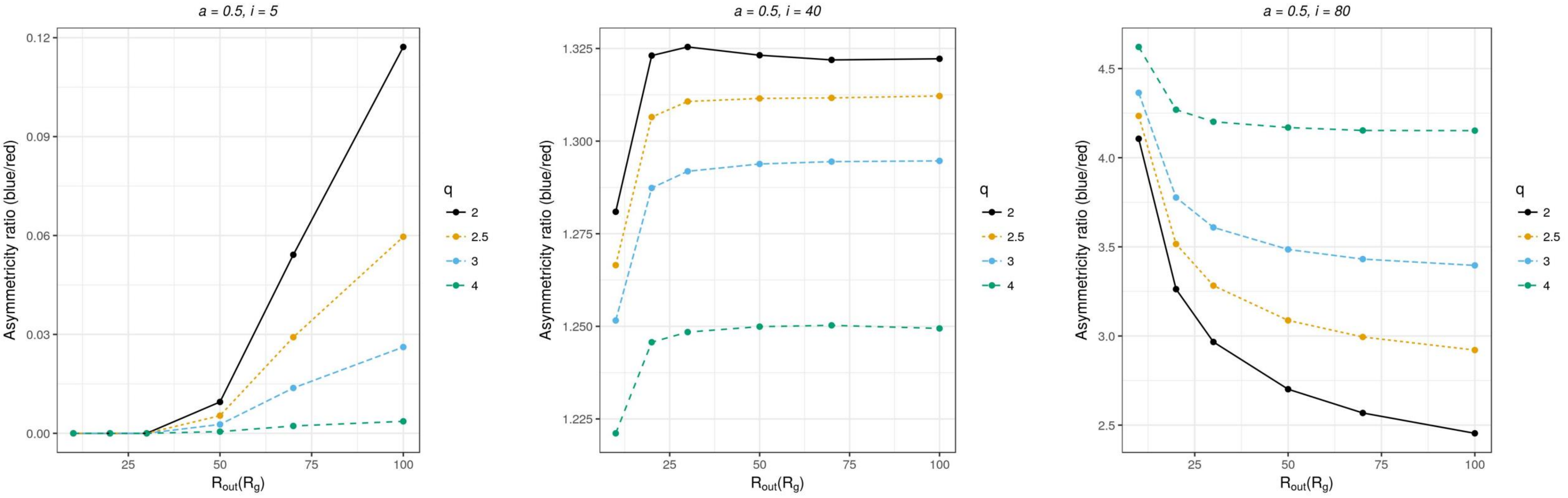
Asymmetric ratio


a = 0.05, i = 5

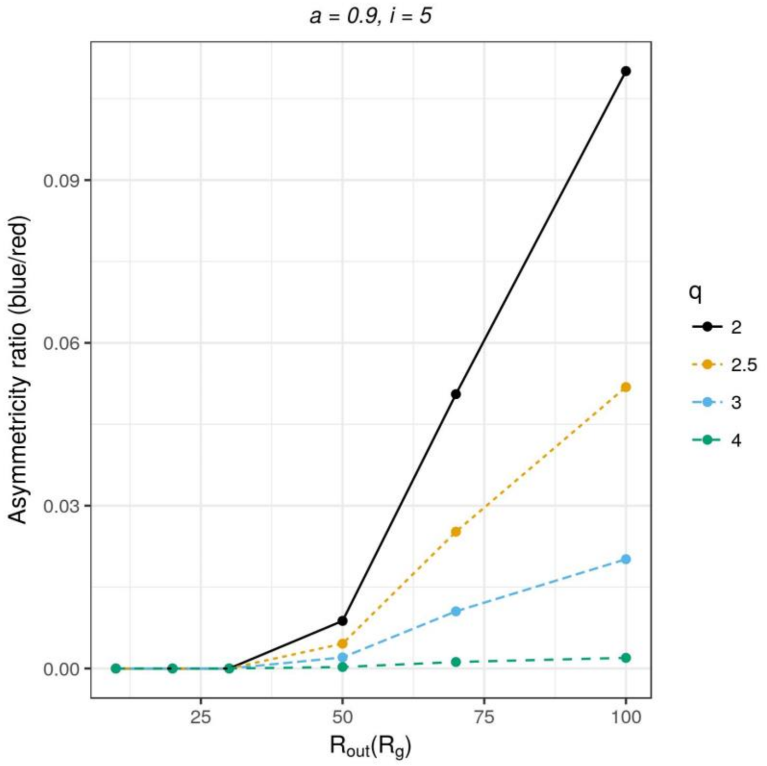

a = 0.05, i = 40

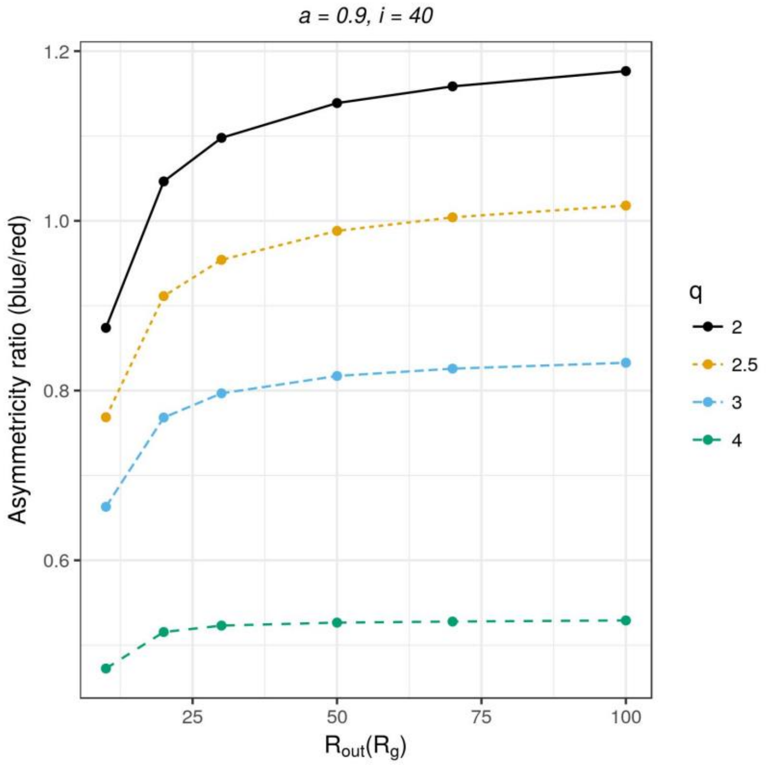

a = 0.05, i = 80

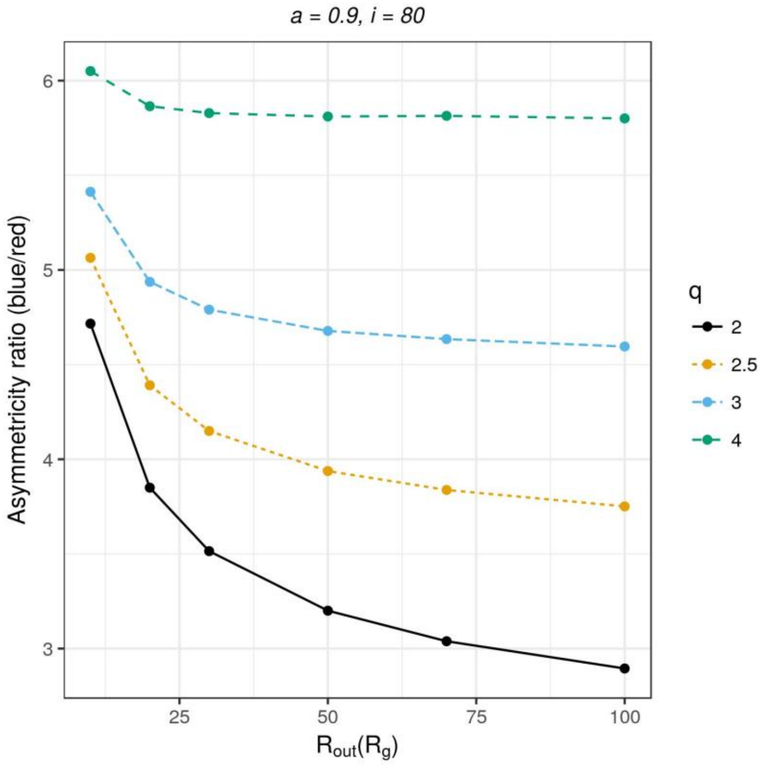
Asymmetric ratio



Asymmetric ratio







Conclusion

- We developed a model of an accretion disk around a SMBH hole using **numerical simulations** based on a ray-tracing method in Kerr metric
- This model allows us to study the radiation which originates in vicinity of the SMBHs
- The **shape of the emitted broad Fe Ka line** is strongly affected by three types of shifts:
  - classical Doppler shift - causing double-peaked profile
  - special relativistic transverse Doppler shift and relativistic beaming - enhancing blue peak relative to red one
  - general relativistic gravitational redshift - smearing blue emission into red one
- Comparisons between the modelled and observed iron Ka line profiles allow us to **determine the parameters of the line emitting region** as well as to study plasma physics and **space-time metrics** in vicinity of SMBHs
- **Two of them** are of especial importance for investigating the strong gravitational field of AGN: **mass** of central BH and its **angular momentum**.
- Other parameters can give us information about the **plasma conditions** in vicinity of the central BH of AGN.