Observational Effects of Strong Gravity in Vicinity of Supermassive Black Holes

Predrag Jovanović and Luka Č. Popović

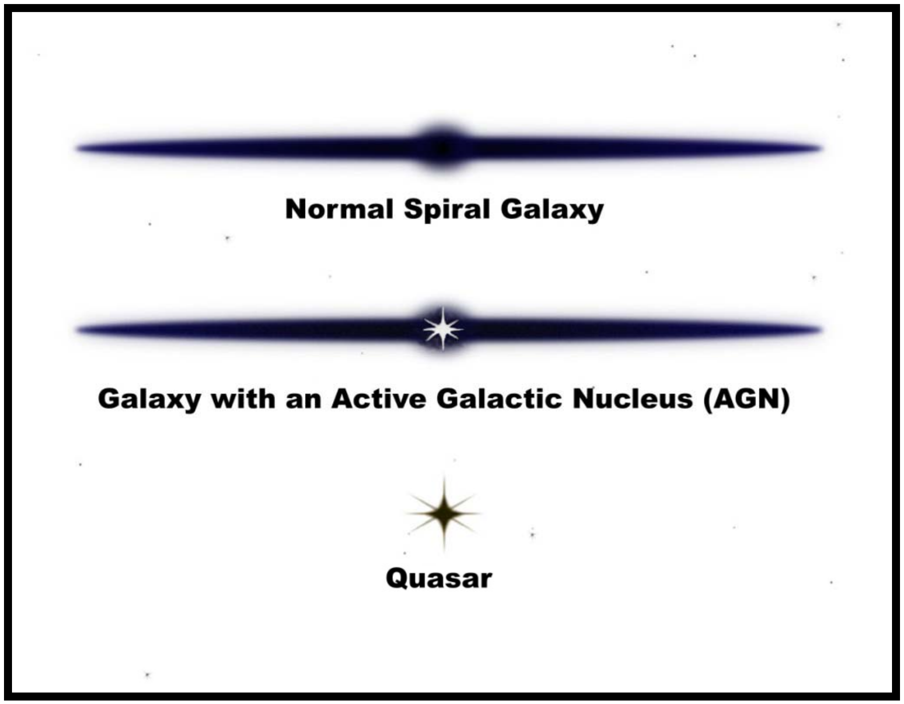
Astronomical Observatory Belgrade, Serbia

Summary of the talk:

- Supermassive black holes as driving engines of Active Galactic Nuclei (AGN) and Quasars
- Standard model of accretion disk
- X-ray radiation from accretion disk around a supermassive black hole (BH): observational effects
- Our recent investigations and results
- Conclusions

Active Galaxies and Quasars

- small highly variable and very bright core embedded in an otherwise typical galaxy



features:

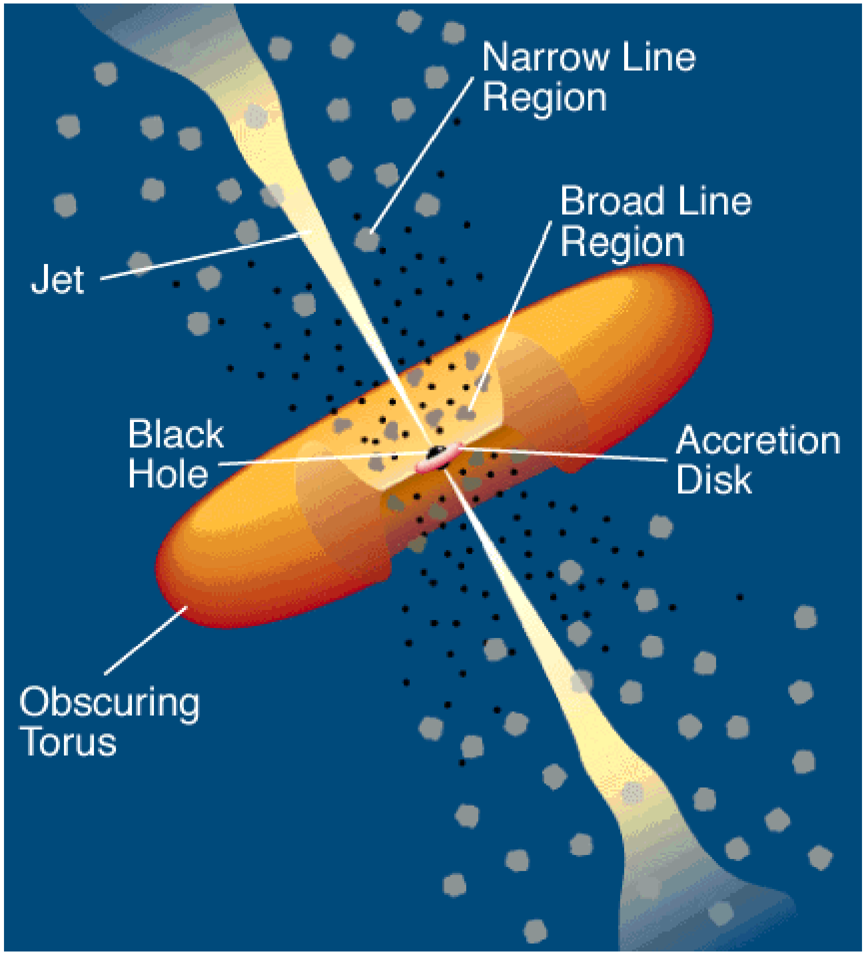
- 10% of all galaxies
- 10^4 times higher luminosity than typical galaxies
- tiny volumes ($\ll$ 1 pc^3)
- radiation in broad range: from γ-rays to radio waves
- very small angular size depending on wavelength
- strong and sometimes very broad emission lines
- variability
- polarization
- radio emission

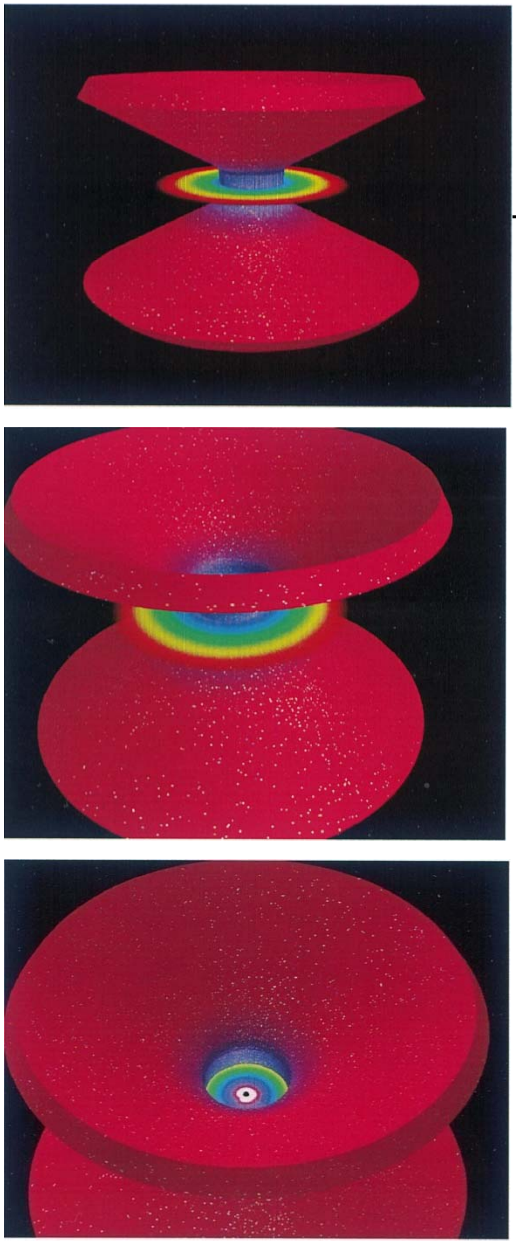
Unified model of AGN

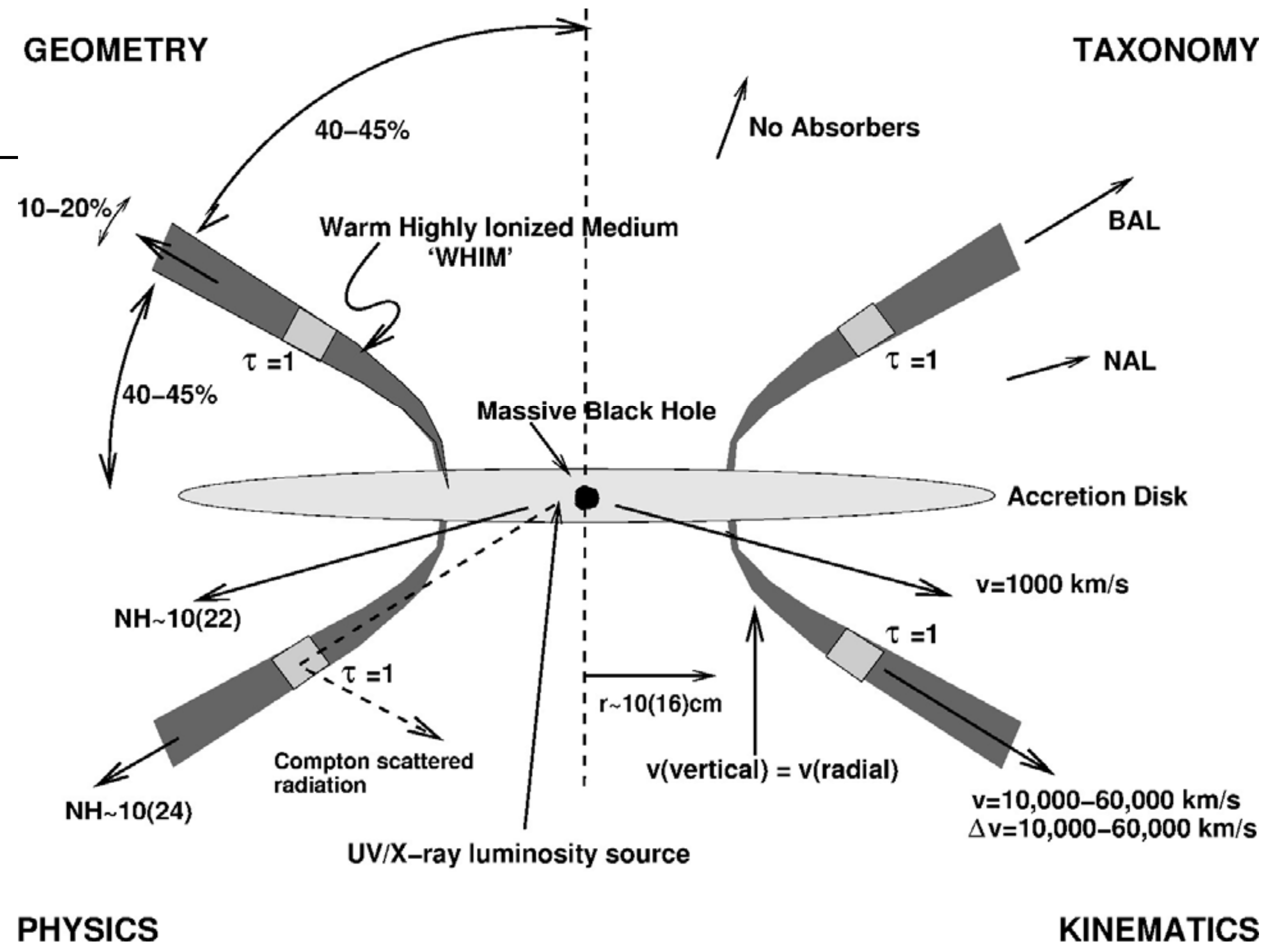
Classification of AGN

- radio-loud galaxies
- radio-quiet galaxies
- broad line radio galaxies
- narrow line radio galaxies
- optically violently variable quasars
- BL Lac objects (blazars)
- Seyfert I galaxies
- Seyfert II galaxies
- LINERs (Low-Ionization Nuclear Emission Regions)

Urry & Padovani 1995, PASP, Vol. 107, No. 715, 803.

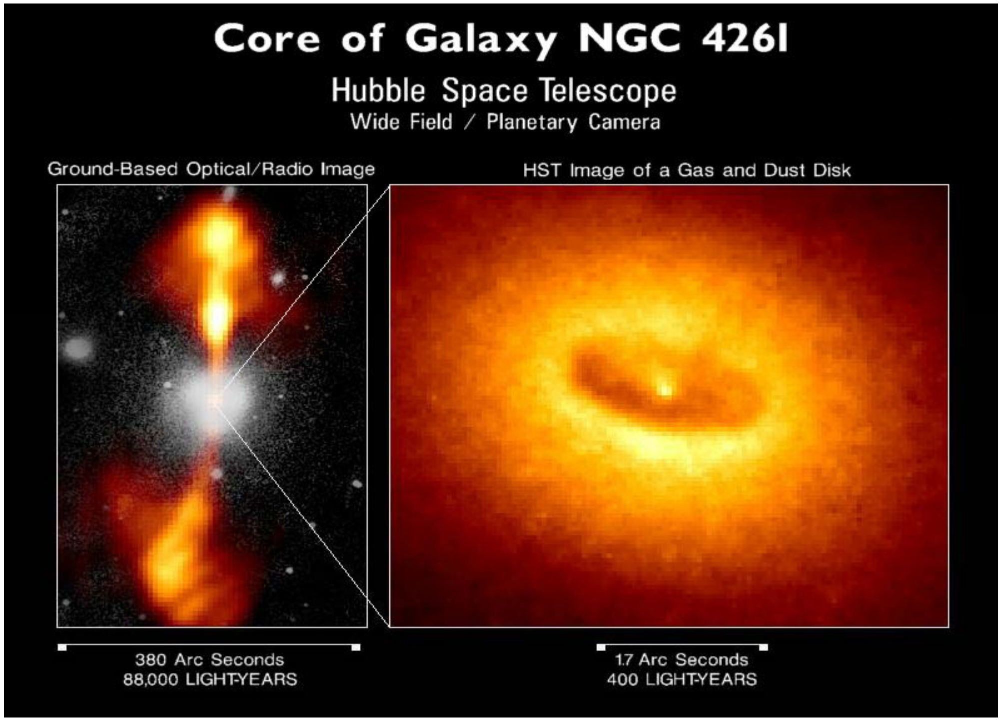


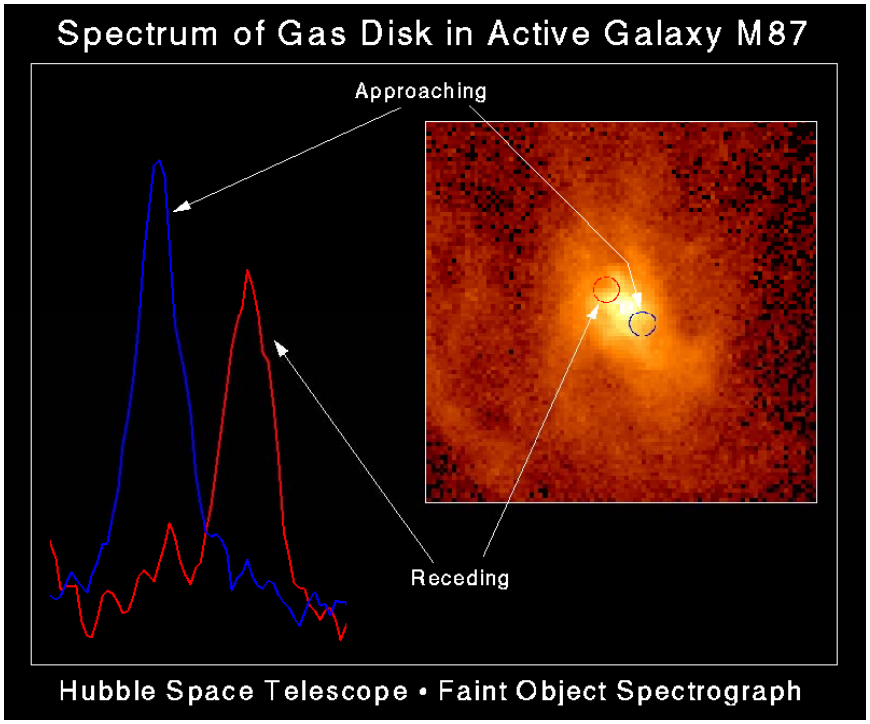




(Martin, E. 2000, ApJ, 545, 63)

Some examples of AGN





Space-time geometry in vicinity of BH

Schwarzschild metric:

$$ds^2 = dt^2\left(1-\frac{1}{r}\right) - dr^2\left(1-\frac{1}{r}\right)^{-1} - r^2\left(d\theta^2 + sin^2\theta d\phi^2\right)$$

Schwarzschild radius:

$$r_s = \frac{2GM}{c^2}$$

Kerr metric:

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

where

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

Standard model of accretion disk

- Optically thick and geometrically thin disk
- power law of disk emissivity:

$$I_P(X,Y) = \varepsilon_0 \cdot r^q(X,Y) \cdot g^4(X,Y)$$

- black-body emissivity law:

$$I_P(X,Y;E) = \frac{2E^3}{h^2c^2}\frac{1}{e^{E/kT(X,Y)}-1}$$

- modifiedblack-body emissivity law:

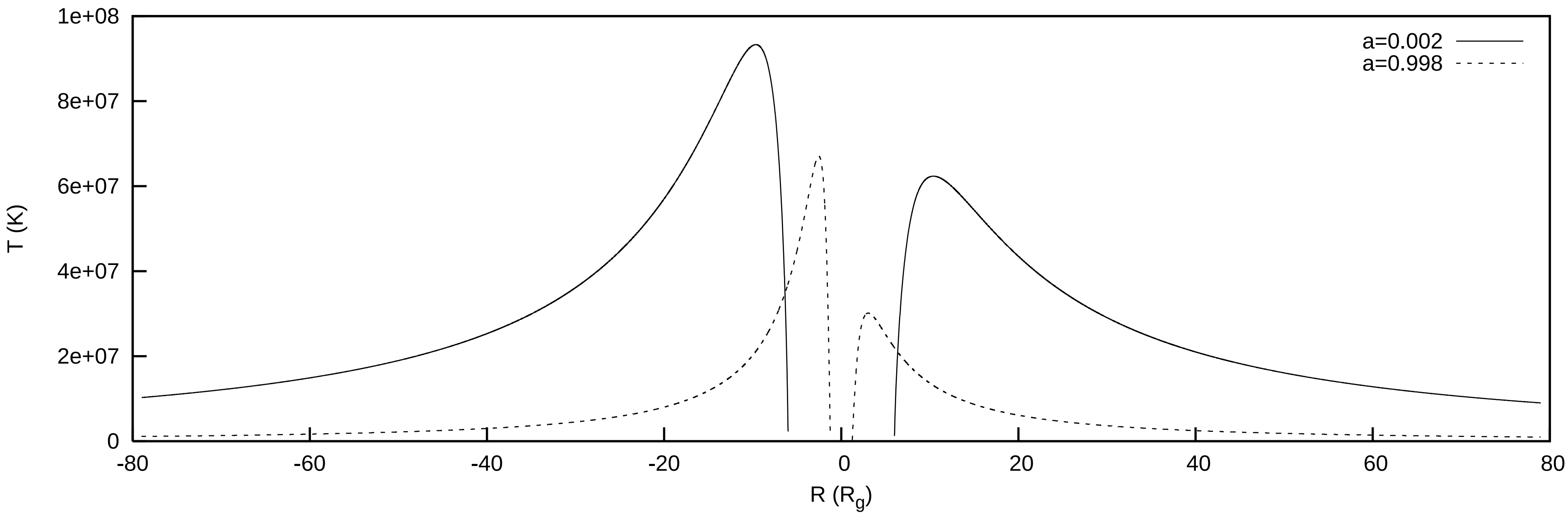
$$I_P(X,Y;E) \propto x^3 e^{-x}, \quad x = \frac{E}{kT(X,Y)}$$

- effective temperature of radiation: 10^7 - 10^8 K

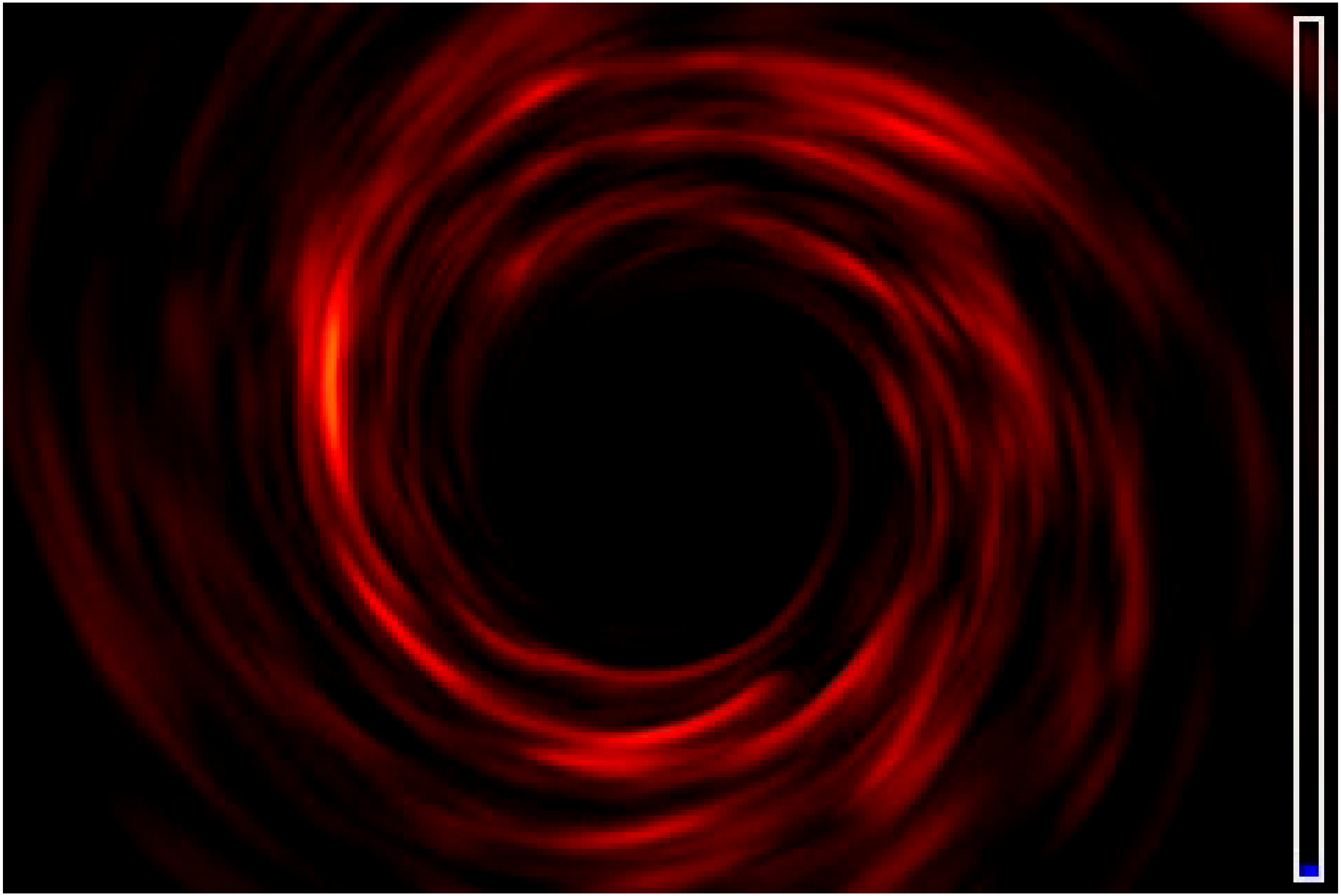
Radial distribution of surface temperature

(Shakura & Sunyaev 1973, *Astron. Astrophys*, **24**, 337)

$$T(X,Y) \sim r^{-\frac{3}{2}}(X,Y)\left(1 - r^{-\frac{1}{2}}(X,Y)\right)^{\frac{4}{5}} \mathrm{K}$$



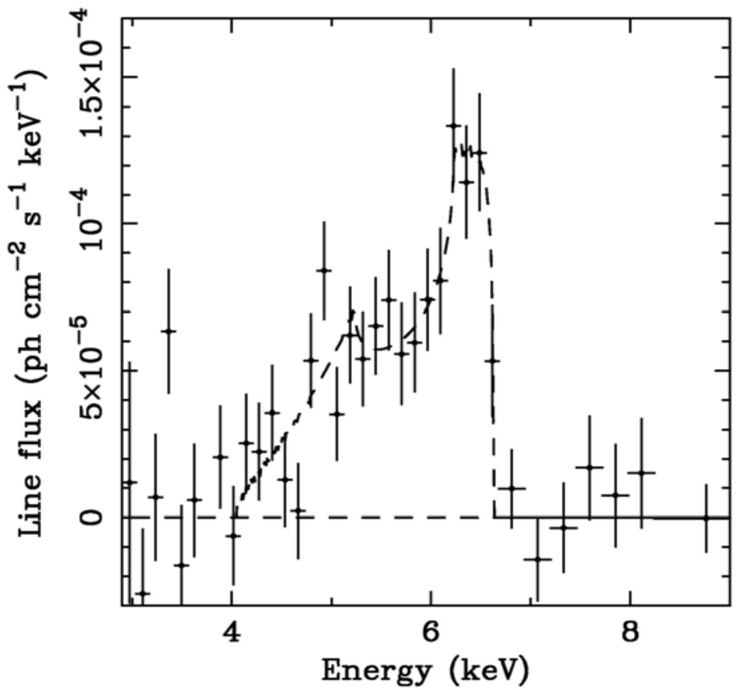
The distribution of the temperature as a function of the radius *R* along the direction of the disk rotation, given for two different values of angular momentum *a*. Negative values of *R* correspond to the approaching and positive values to the receding side of the disk.



X-ray radiation from accretion disks of AGN

1. **<u>in continnum</u>**: 0.1 – 100 keV
- soft and hard component
- variations: from several part of an hour until several days

2. **<u>in Fe Kα line:</u>**
- broad emission line on 6.4 keV
- asymetric profile with narrow bright **blue** peak and wide faint **red** peak
- Line width corresponds to velocity:
  - v ~ 80000 – 100000 km/s (MCG-6-30-15)
  - v ~ 48000 km/s (MCG-5-23-16)
  - v ~ 20000 – 30000 km/s (many other AGN)
- variability of both: line shape and intensity



MCG-6-30-15, ASCA SIS
(Tanaka et al. *Nature*, 1995, **375**, 659.)

Ray-tracing in Kerr metric

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

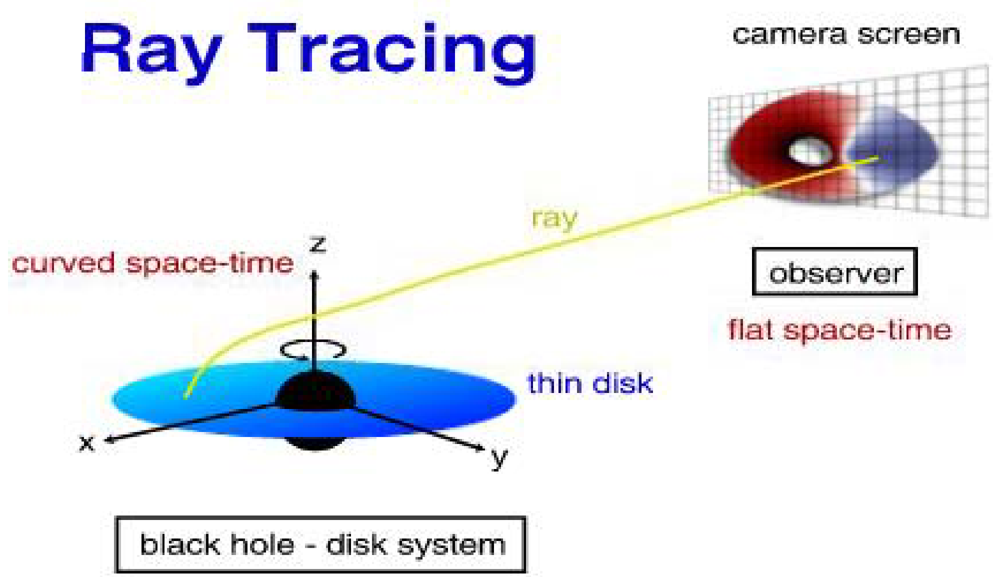
$$R(r,\lambda,q) = \left\{(r^2 + a^2 - a\lambda)^2 - \Delta[(\lambda - a)^2 + q^2]\right\}$$

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

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

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

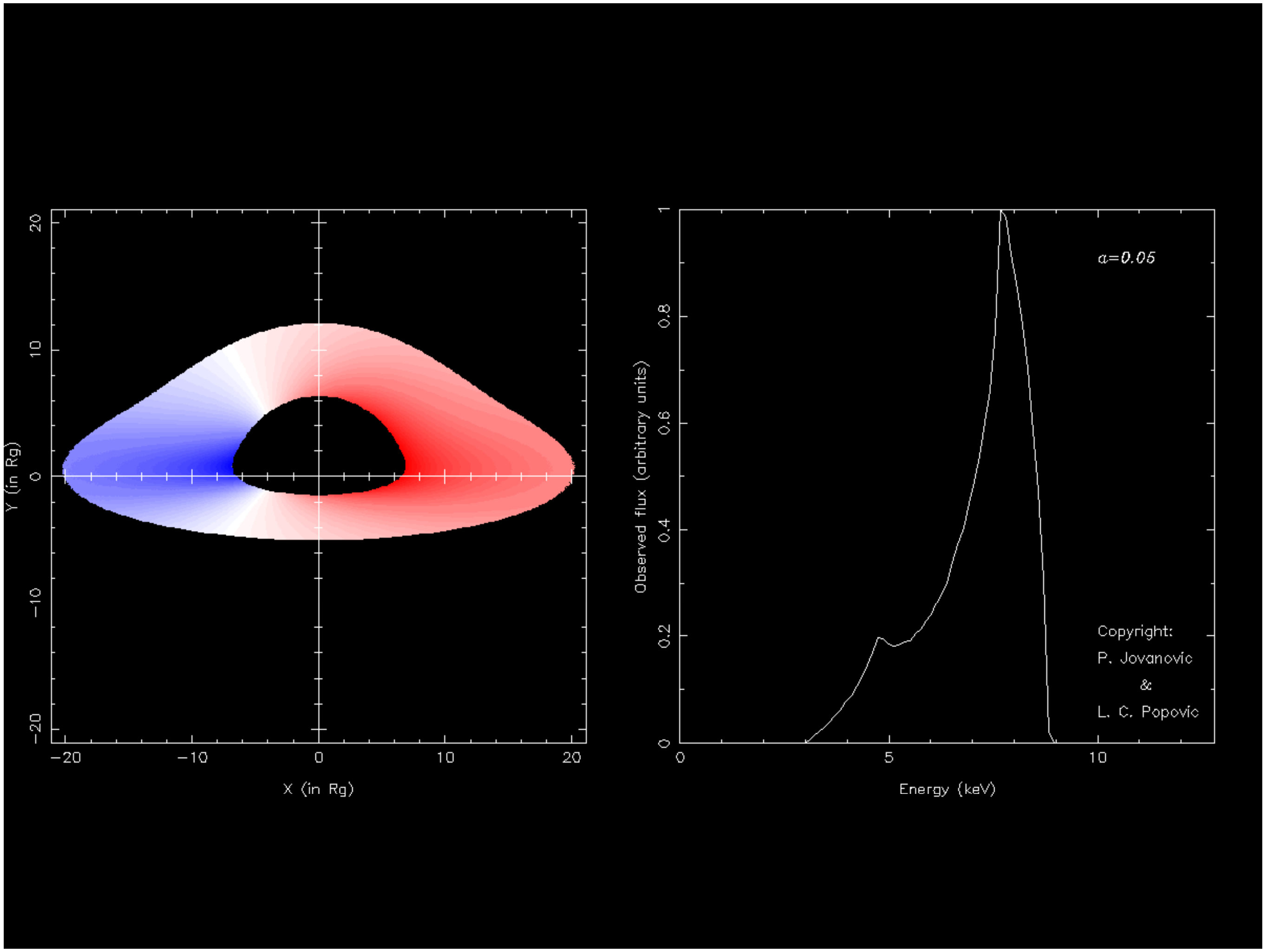
$$F_{\rm obs}(E_{\rm obs}) = \int_{\rm image} \epsilon(r) g^4 \delta(E_{\rm obs} - gE_0)\, d\Xi$$



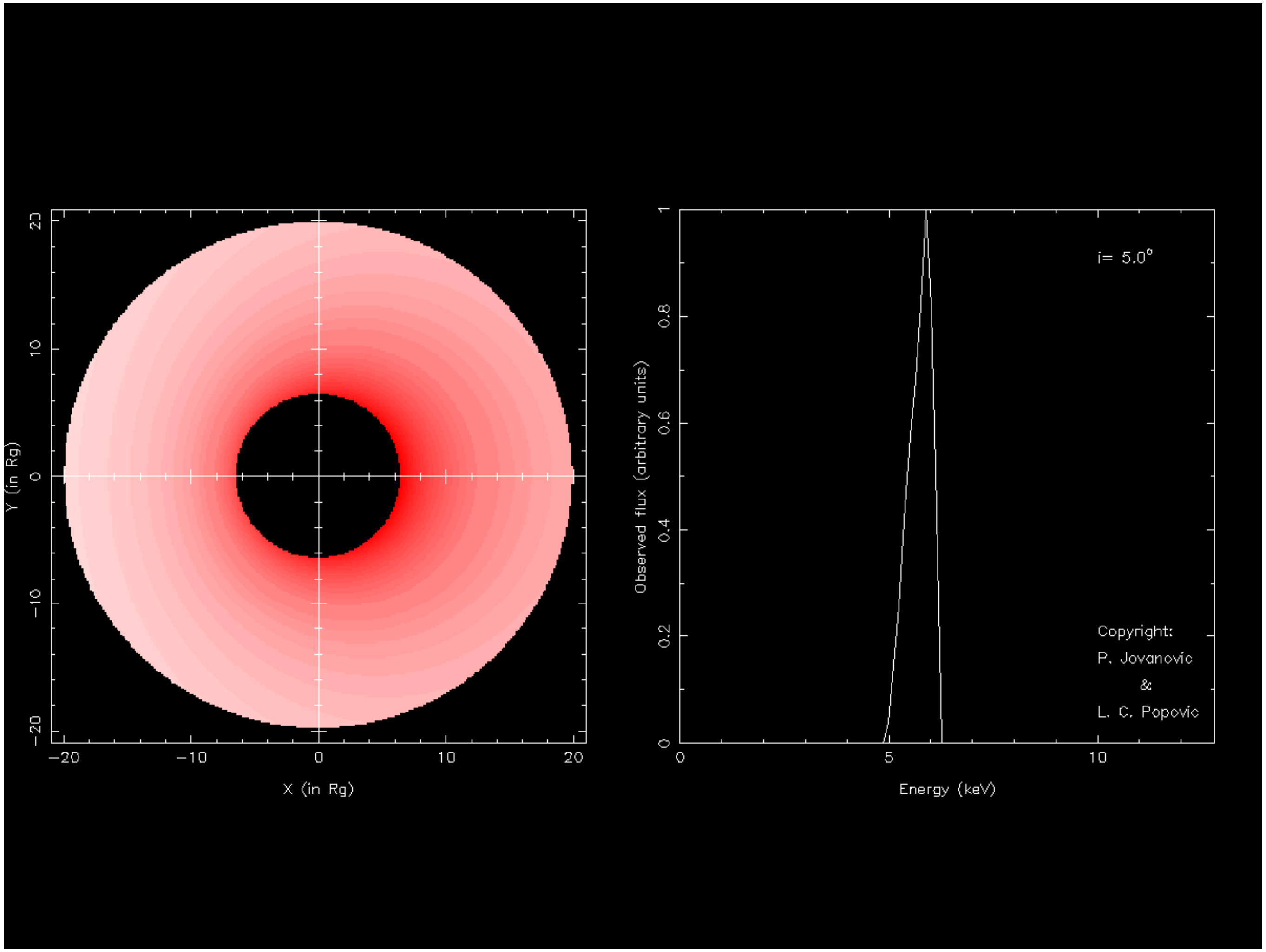
Our recent investigations and results

1. Modeling of emission of accretion disk around supermassive BH using numerical simulations based on a ray-tracing method
2. Investigation of the effects of strong gravitational field by comparison between modeled and observed iron Kα line profiles
3. Scanning the innermost parts of accretion disks by gravitational microlensing: variations of the Kα line profile

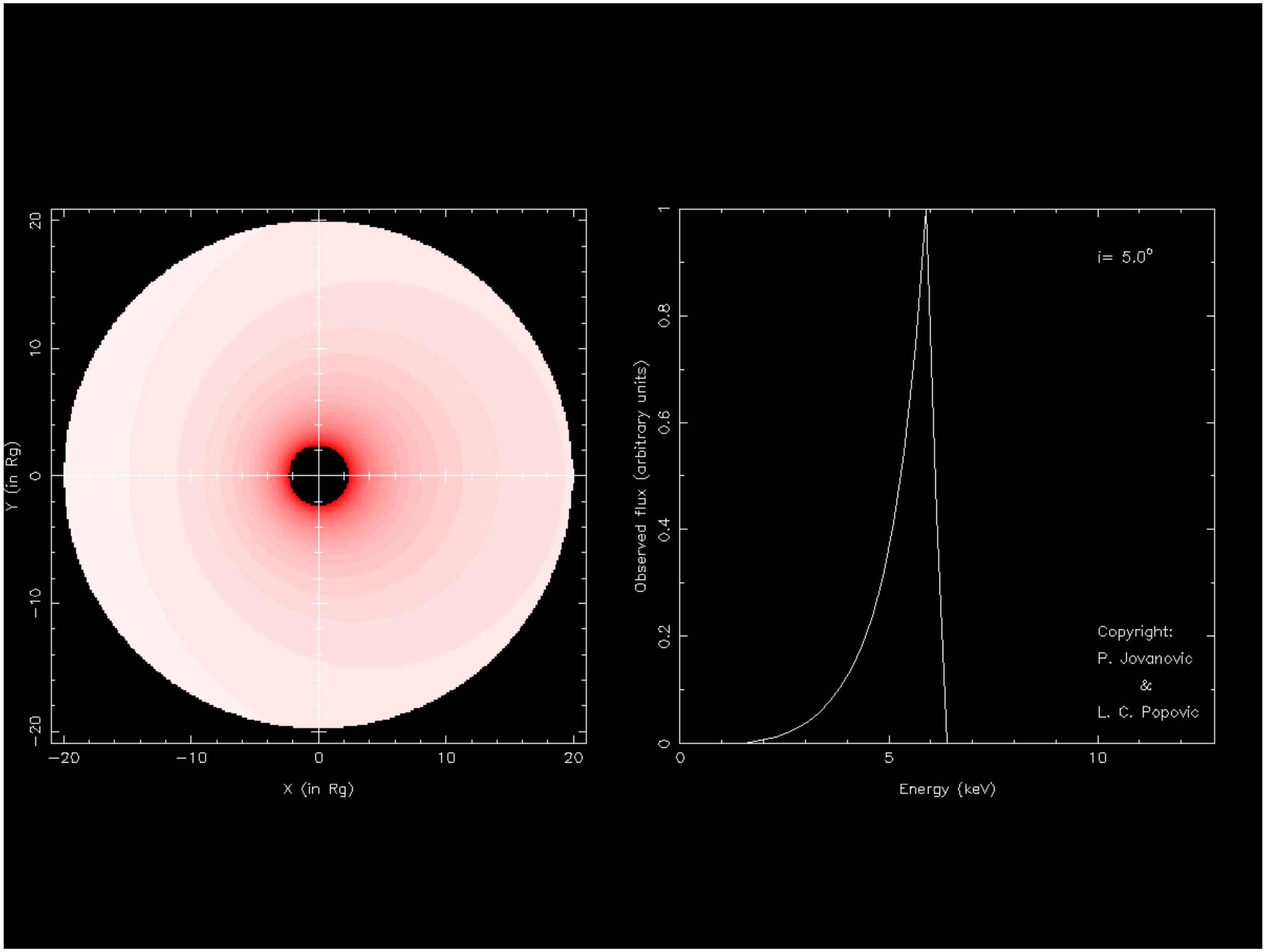
Numerical simulations of a highly inclined accretion disk (i=75°) for different values of angular momentum parameter a (left) and the corresponding profiles of the Fe Kα line (right)

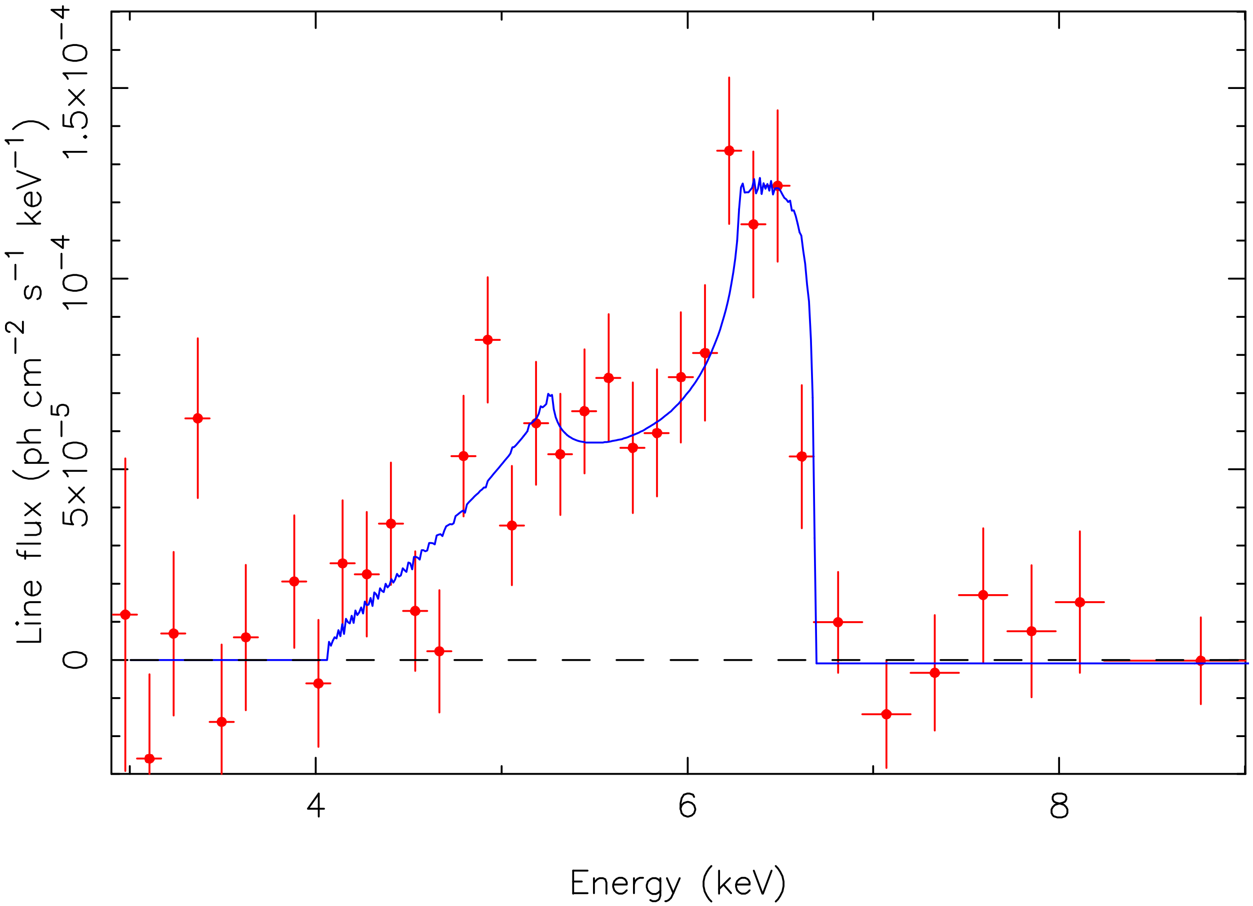


Numerical simulations of an accretion disk in Schwarzschild metric for different inclination angles *i* (left) and the corresponding profiles of the Fe Kα line (right)



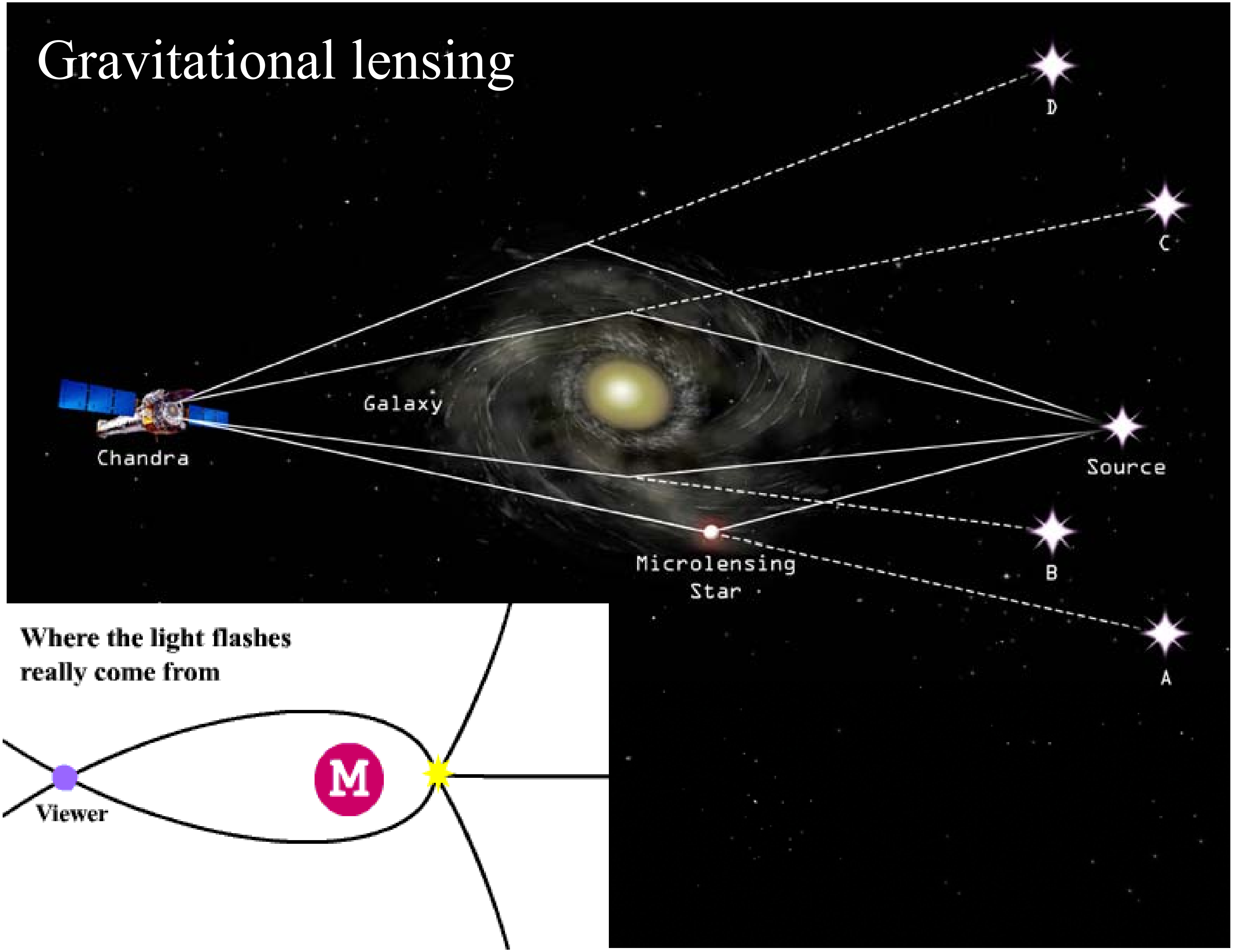
Numerical simulations of an accretion disk in Kerr metric with angular momentum parameter a = 0.998 for different inclination angles i (left) and the corresponding profiles of the Fe Kα line (right)





The Fe Kα line profile from Seyfert I galaxy MCG-6-30-15 observed by the ASCA satellite (Tanaka, Y. et al, 1995, *Nature*, **375**, 659). The solid line shows the modeled profile expected from an accretion disk extending between 6 and 20 R_g around Schwarzschild BH.

Gravitational lensing



Gravitational microlensing influence on disk emission

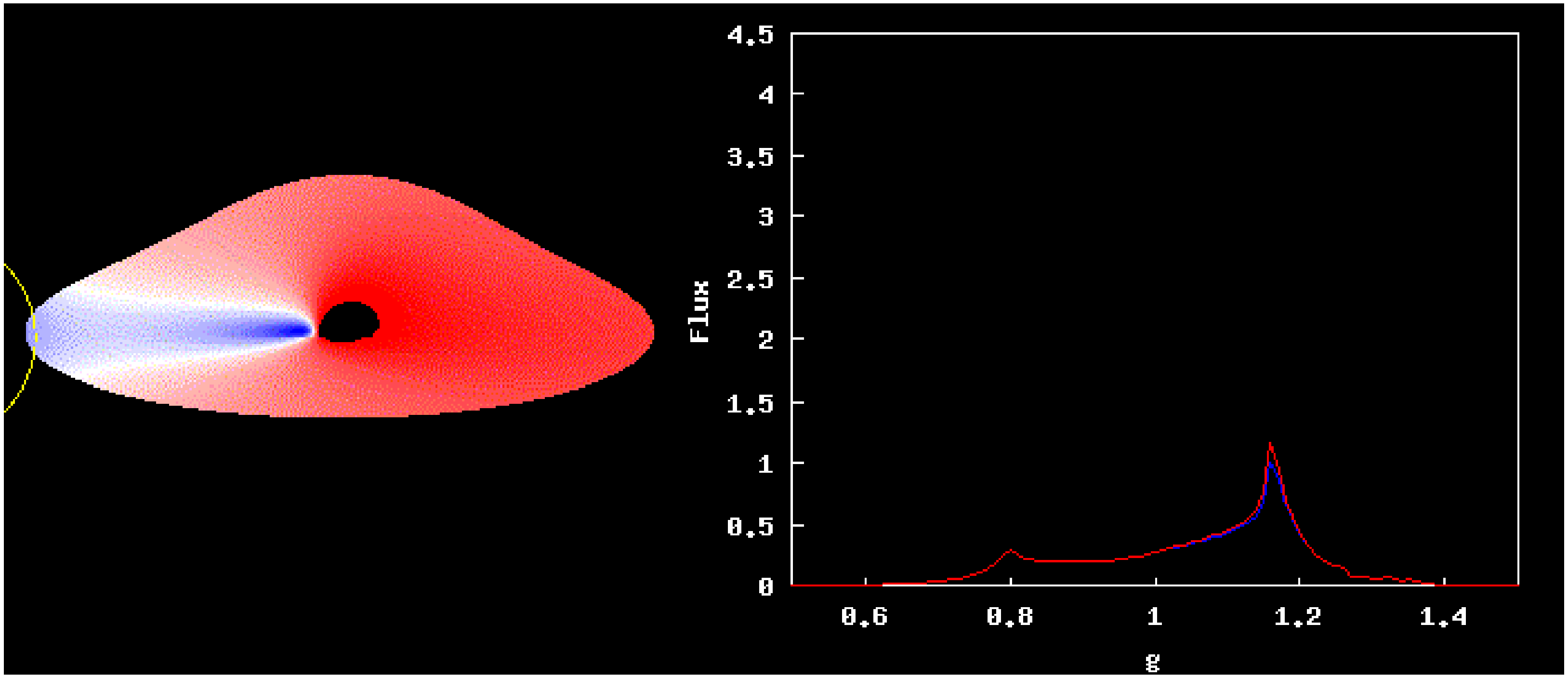
amplification of a point-like microlens: $$A(X,Y) = \frac{u^2(X,Y)+2}{u(X,Y)\sqrt{u^2(X,Y)+4}}$$

amplification of a caustic microlens: $$A(X,Y) = A_0 + \frac{K}{\sqrt{\kappa(\xi-\xi_c)}} \cdot H(\kappa(\xi-\xi_c)).$$

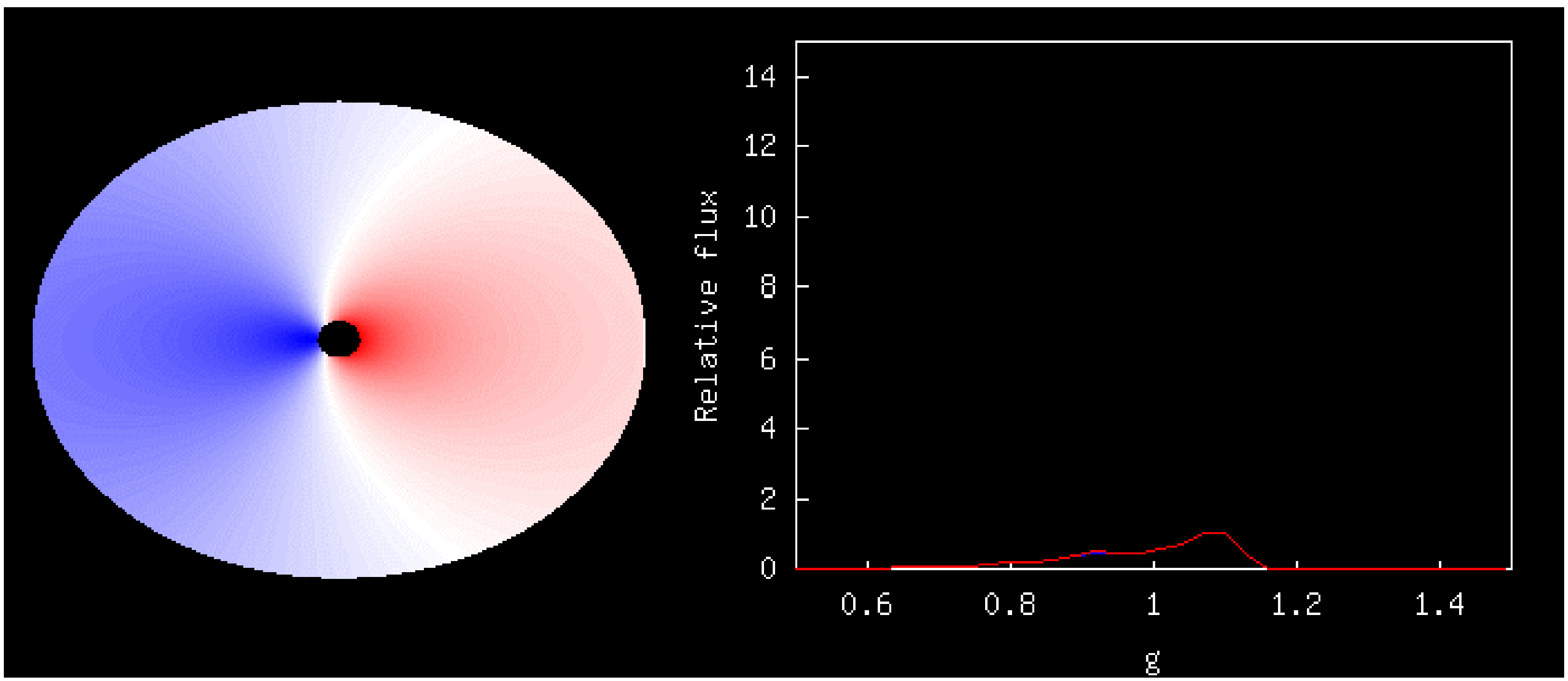
amplified brightness: $I_p = \varepsilon(r)g^4(X,Y)\delta(x-g(X,Y))A(X,Y),$ $g = \nu_{obs}/\nu_0$

total observed flux: $$F(x) = \int_{\text{image}} I_p(x)\mathrm{d}\Omega.$$

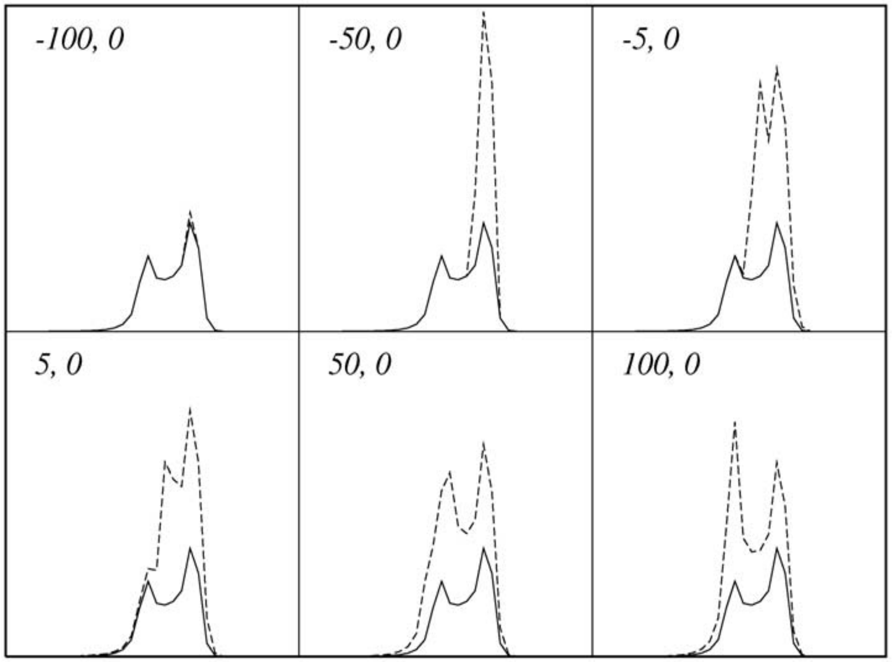
where $d\Omega$ is the solid angle subtended by the disc in the observer's sky

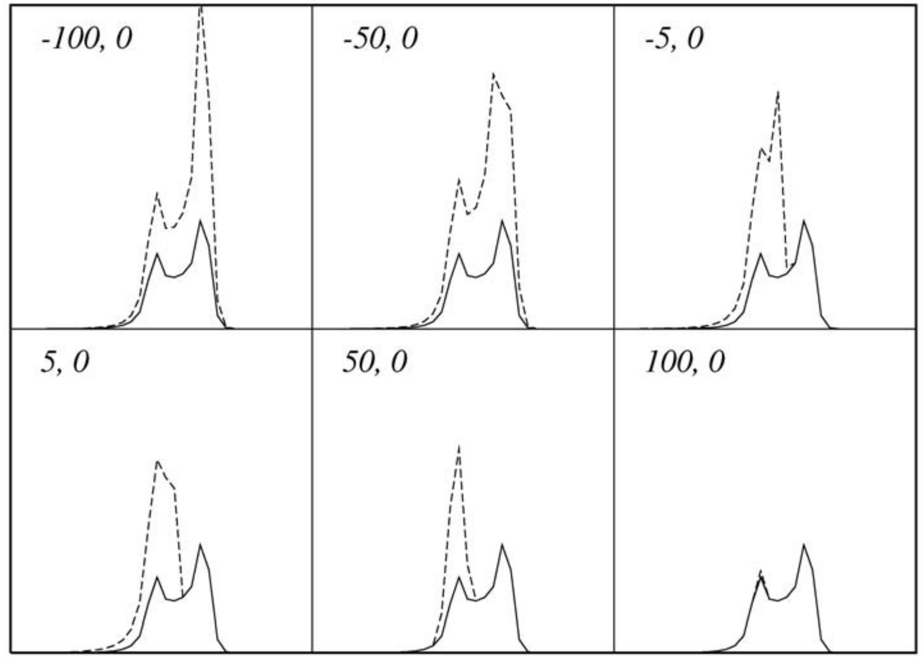


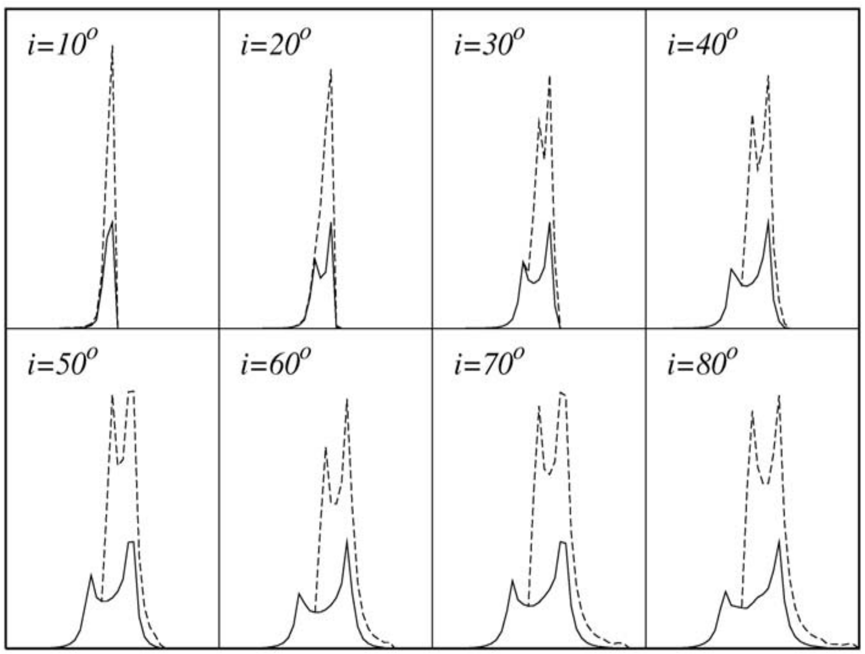
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Flux
0.6
0.8
1
1.2
1.4
g

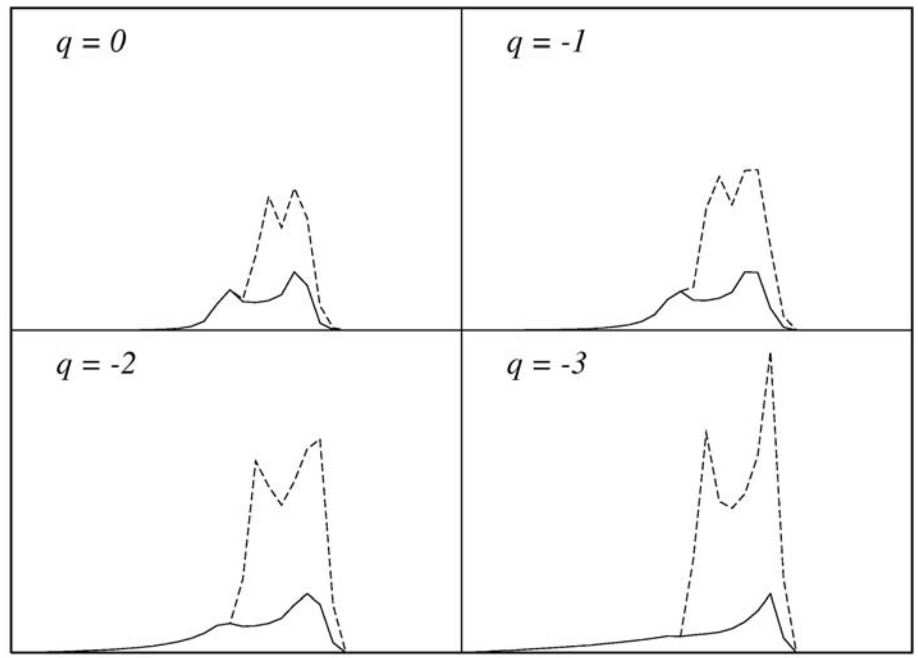


14
12
10
8
6
4
2
0
Relative flux
0.6
0.8
1
1.2
1.4
g


-100, 0
-50, 0
-5, 0
5, 0
50, 0
100, 0


-100, 0
-50, 0
-5, 0
5, 0
50, 0
100, 0


i=10°
i=20°
i=30°
i=40°
i=50°
i=60°
i=70°
i=80°


q = 0
q = -1
q = -2
q = -3

Conclusions

- Comparisons between the modeled and observed iron Kα line profiles allow us to determine the parameters of the line emitting region.
- Two of them are of especial importance for investigating the strong gravitational field of AGN: mass of central BH and its angular momentum.
- Our results show that these parameters have significant influence on Fe Kα line profile and thus, allow us to determine the space-time geometry (metric) in vicinity of the central BH of AGN.
- Other parameters can give us information about the plasma conditions in these regions.
- Gravitational microlensing is a useful tool for revealing the structure and physics of the innermost parts of accretion disks in AGN, close to their central supermassive black holes.

References

1. P. Jovanović, *Publ. Astron. Soc. Pacific 118 (2006) p. 656*
2. L. Č. Popović, E. G. Mediavilla, P. Jovanović & J. A. Muñoz, *Astron. Astrophys. 398 (2003) p. 975*
3. L. Č. Popović, P. Jovanović, E. G. Mediavilla & J. A. Muñoz, *Astron. Astrophys. Trans. 22 (2003) p. 719*
4. L. Č. Popović, P. Jovanović, E. G. Mediavilla, A. F. Zakharov, C. Abajas, J. A. Muñoz & G. Chartas, *Astrophys. J. 637 (2006) p. 620*
5. A. F. Zakharov, L. Č. Popović & P. Jovanović, *Astron. Astrophys.* 420 (2004) p. 881

Thank you for attention!