

# Observational Effects of Strong Gravity in Vicinity of Supermassive Black Holes

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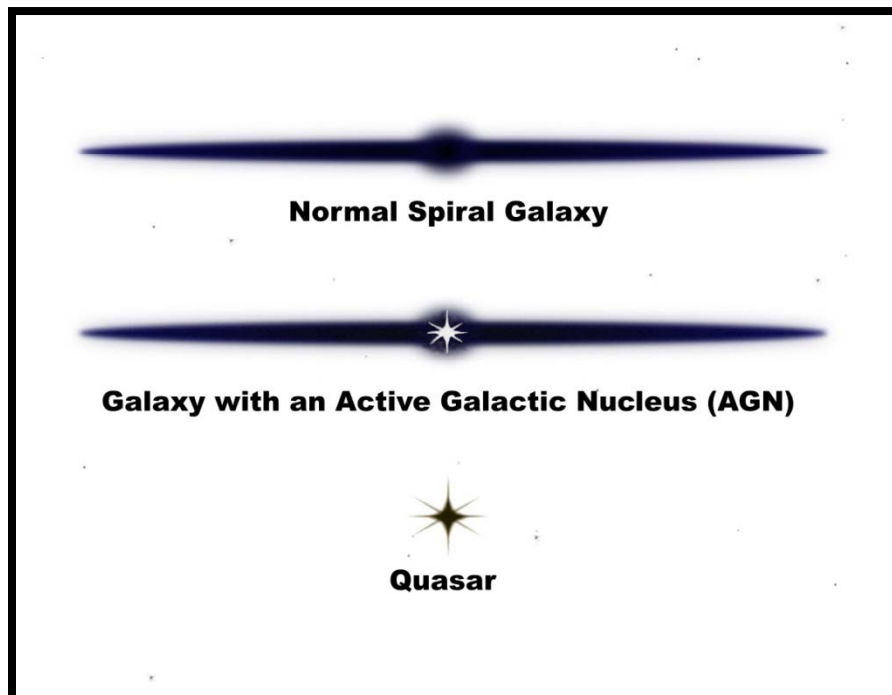
# Summary of the talk:

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- 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:

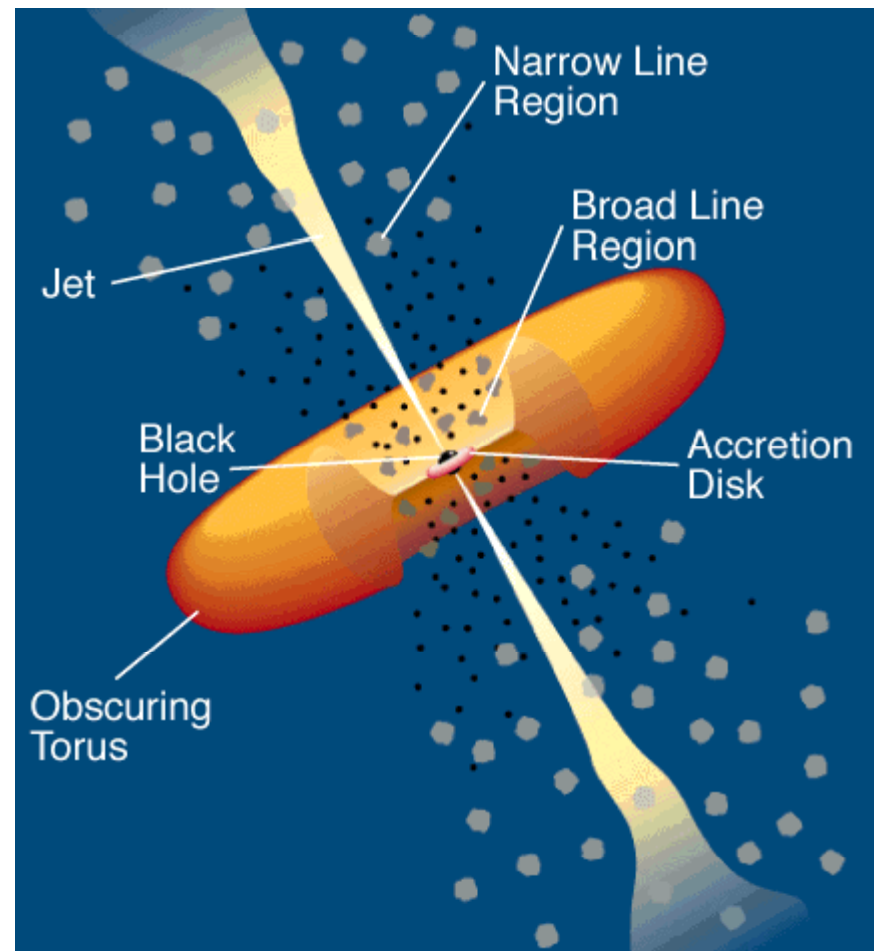
- 10% of all galaxies
- $10^4$  times higher luminosity than typical galaxies
- tiny volumes ( $\ll 1 \text{ pc}^3$ )
- radiation in broad range: from  $\gamma$ -rays to radio waves
- very small angular size depending on wavelength
- strong and sometimes very broad emission lines
- variability
- polarization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

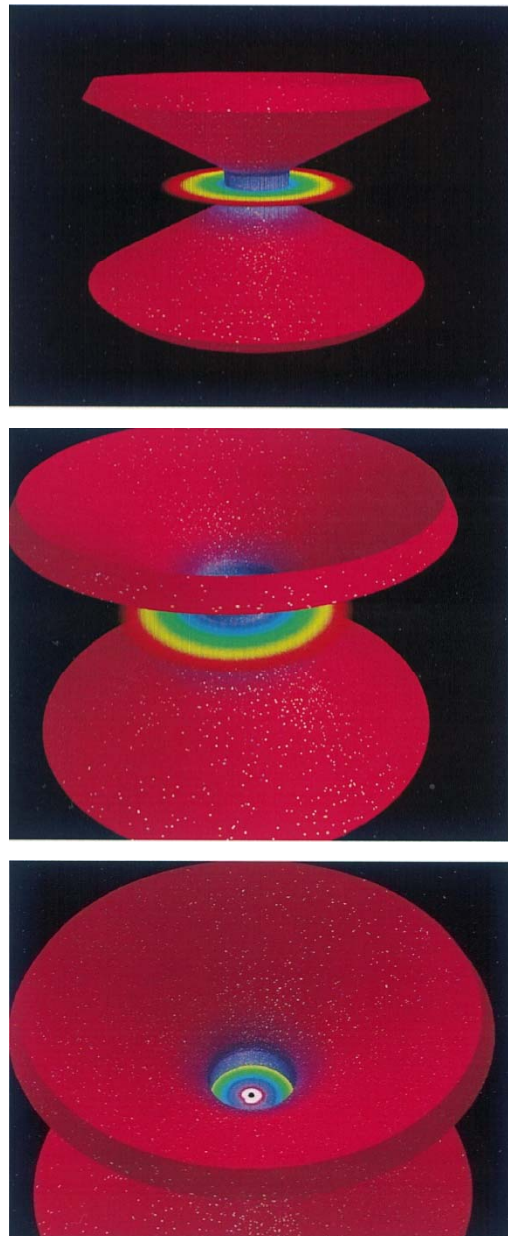
# Unified model of AGN

## 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)

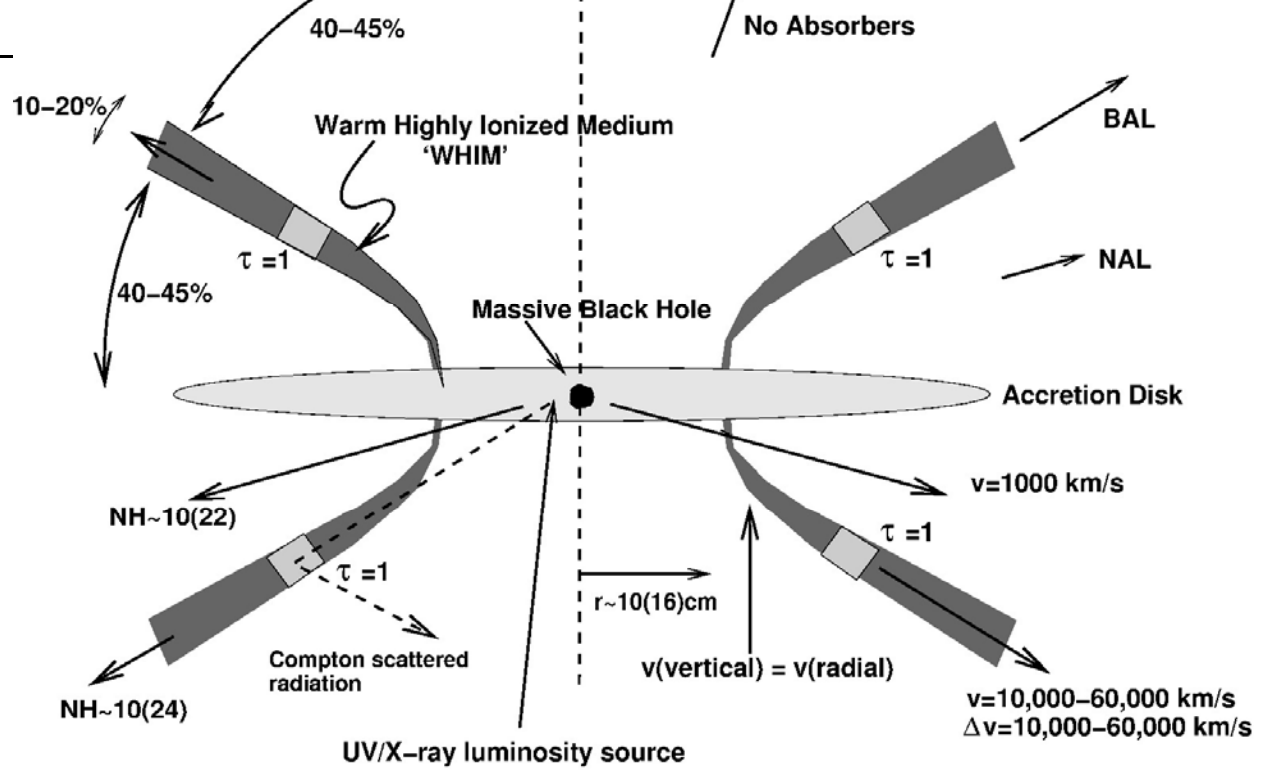
**Urry & Padovani 1995, PASP, Vol. 107, No. 715, 803.**





**GEOMETRY**

**TAXONOMY**

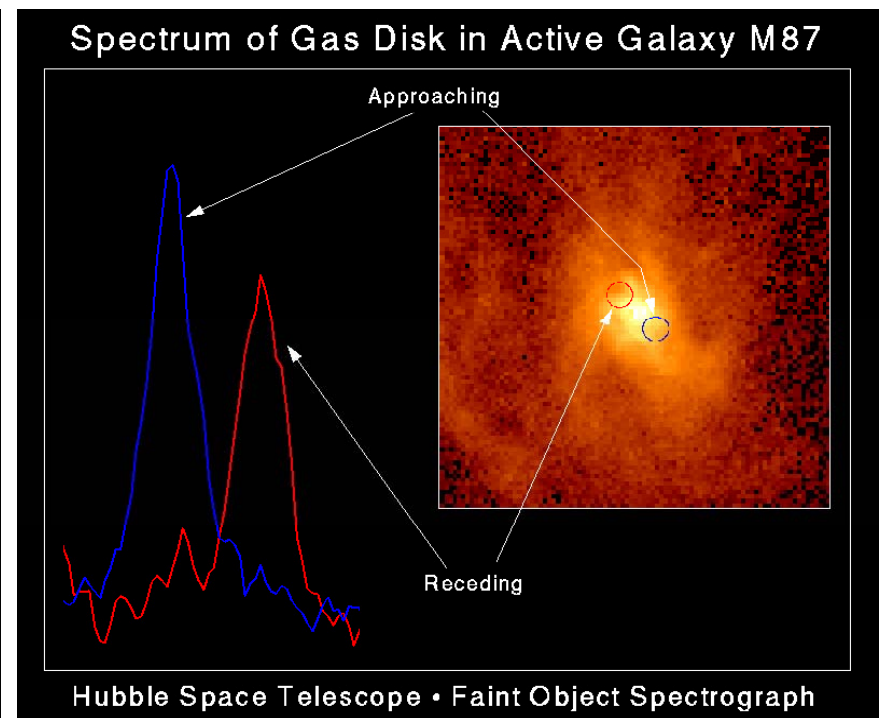
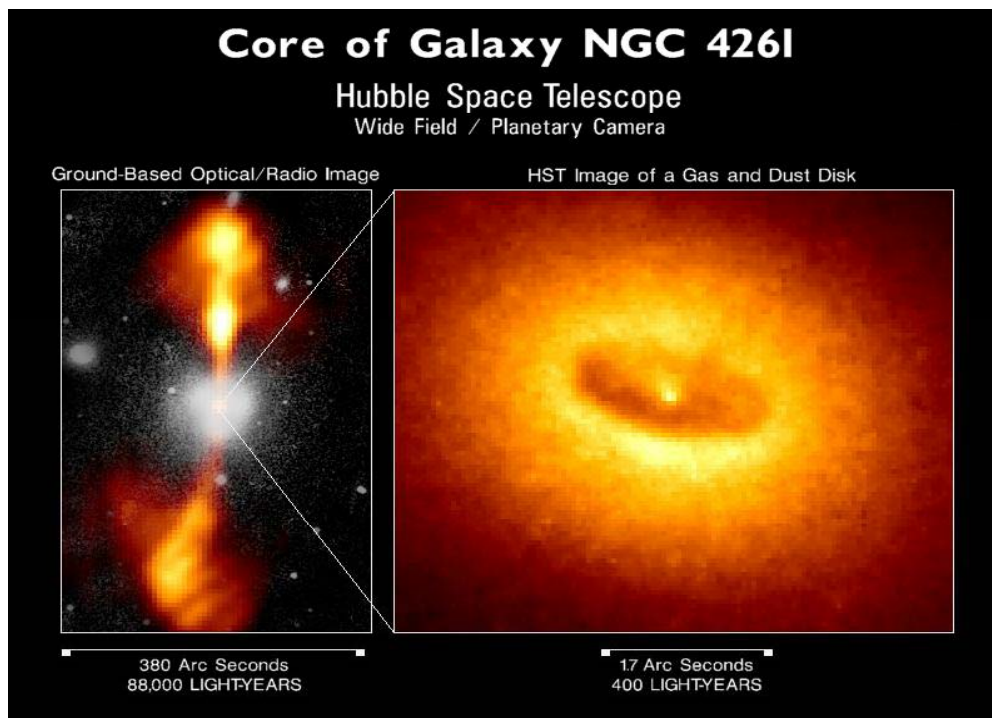


**PHYSICS**

**KINEMATICS**

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

# Some examples of AGN







# Space-time geometry in vicinity of BH

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Schwarzschild metric:

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

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

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

# Standard model of accretion disk

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- 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:

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

- modified black-body emissivity law:

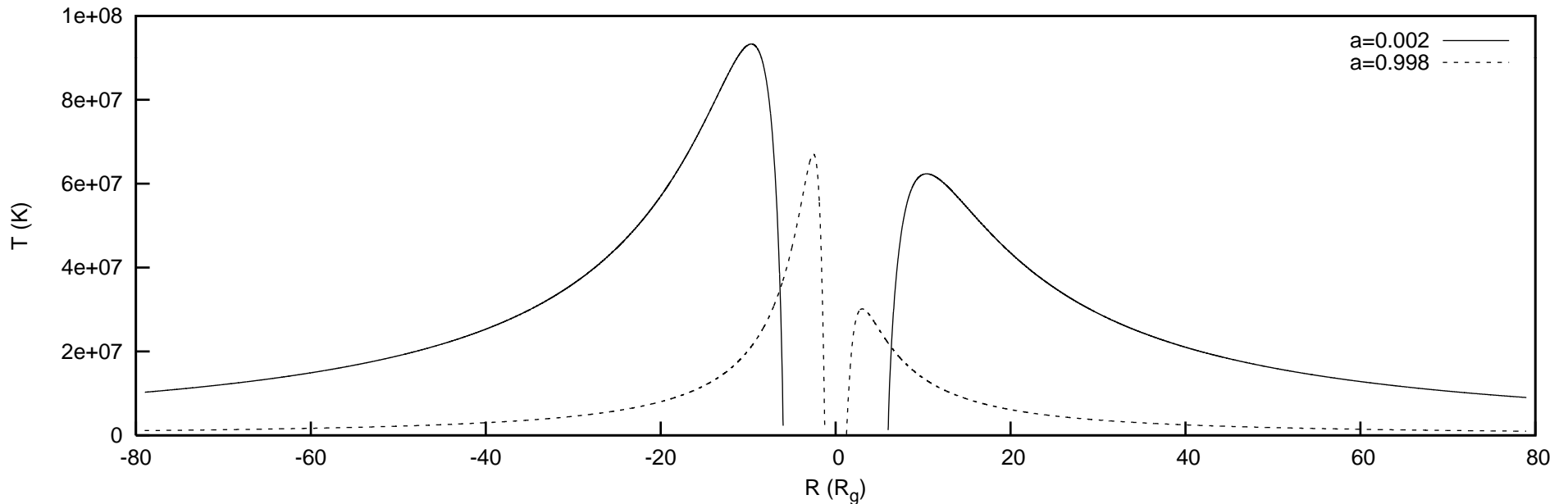
$$I_P(X, Y; E) \propto x^3 e^{-x}, \quad x = \frac{E}{kT(X, Y)}$$

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

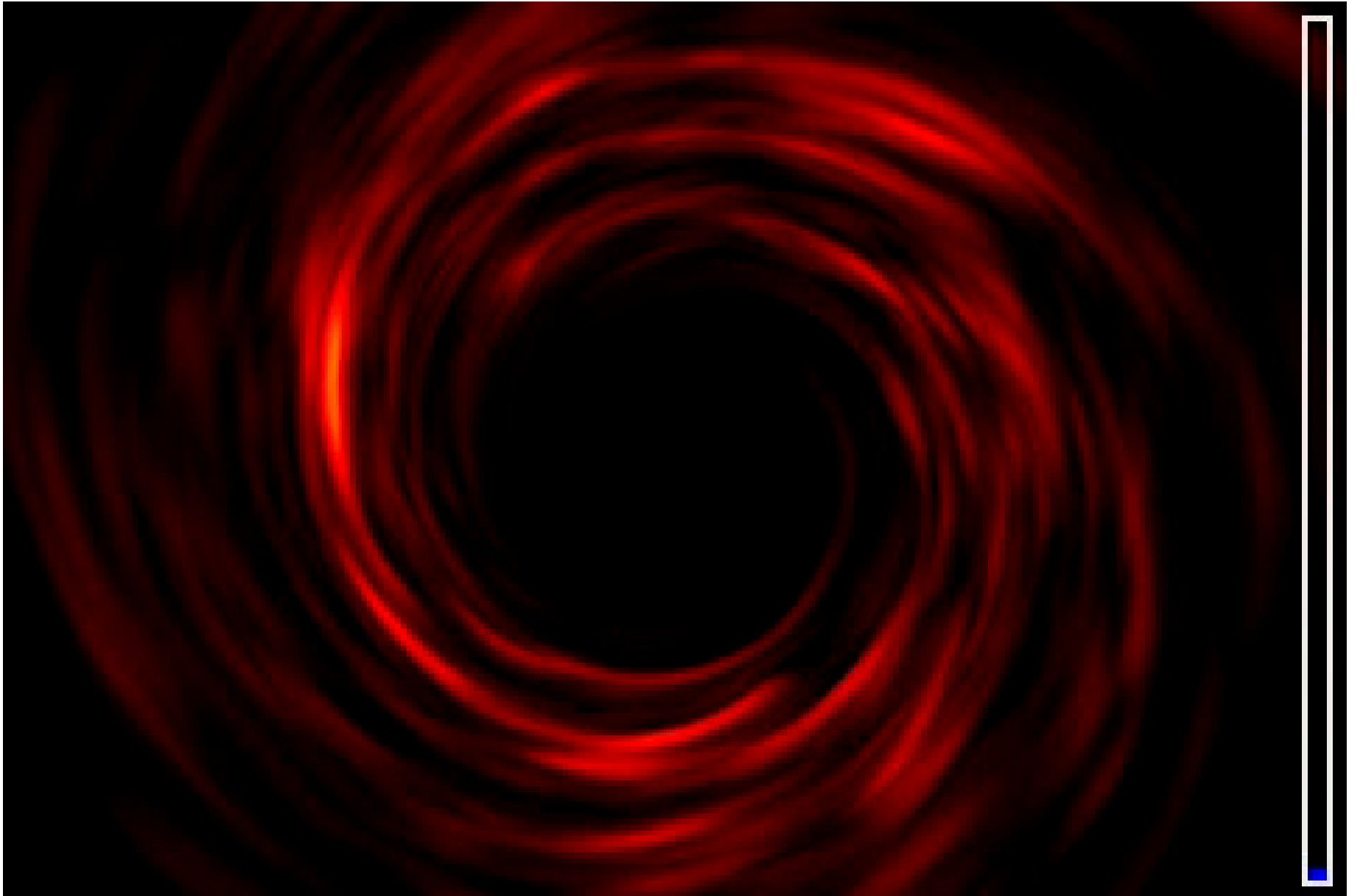
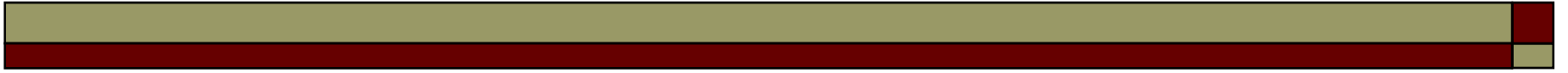
# Radial distribution of surface temperature

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

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

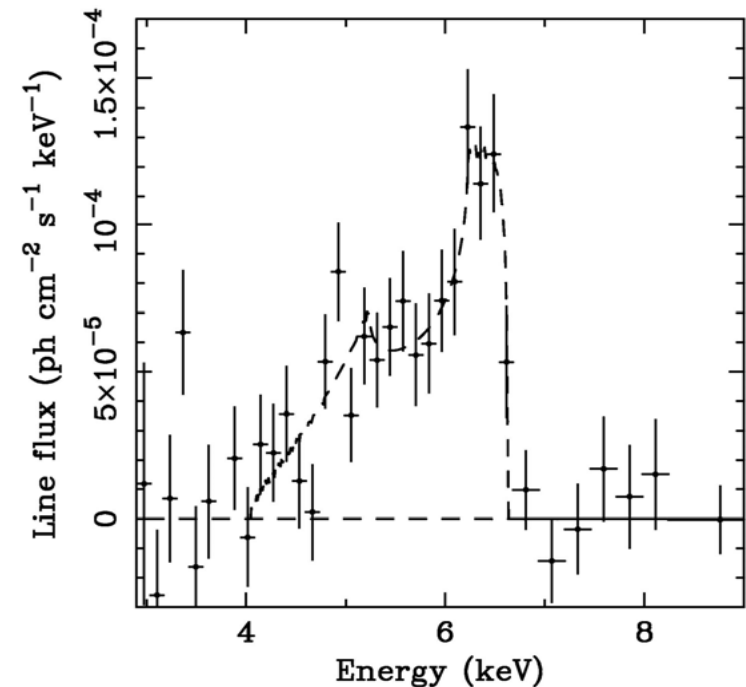


The distribution of the temperature as a function of the radius  $R$  along the direction of the disk rotation, given for two different values of angular momentum  $a$ . Negative values of  $R$  correspond to the approaching and positive values to the receding side of the disk.



# X-ray radiation from accretion disks of AGN

1. **in continuum**: 0.1 – 100 keV
  - soft and hard component
  - variations: from several part of an hour until several days
2. **in Fe K $\alpha$  line**:
  - broad emission line on 6.4 keV
  - asymmetric profile with narrow bright **blue** peak and wide faint **red** peak
  - Line width corresponds to velocity:
    - $v \sim 80000 - 100000$  km/s (MCG-6-30-15)
    - $v \sim 48000$  km/s (MCG-5-23-16)
    - $v \sim 20000 - 30000$  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

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

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

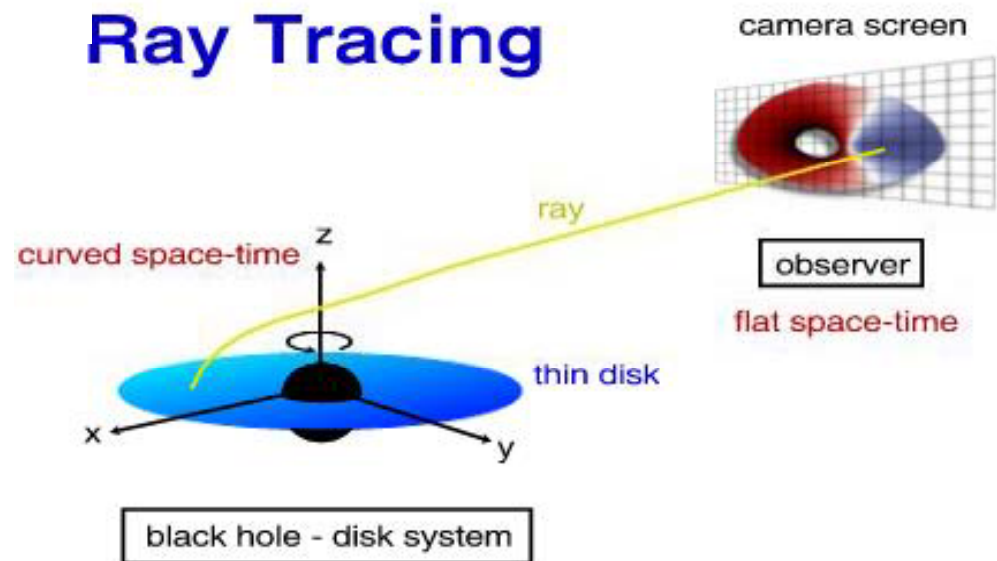
$$\Theta(\theta, \lambda, q) = [q^2 + (a \cos \theta)^2 - (\lambda \cot \theta)^2]$$

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

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

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

## Ray Tracing



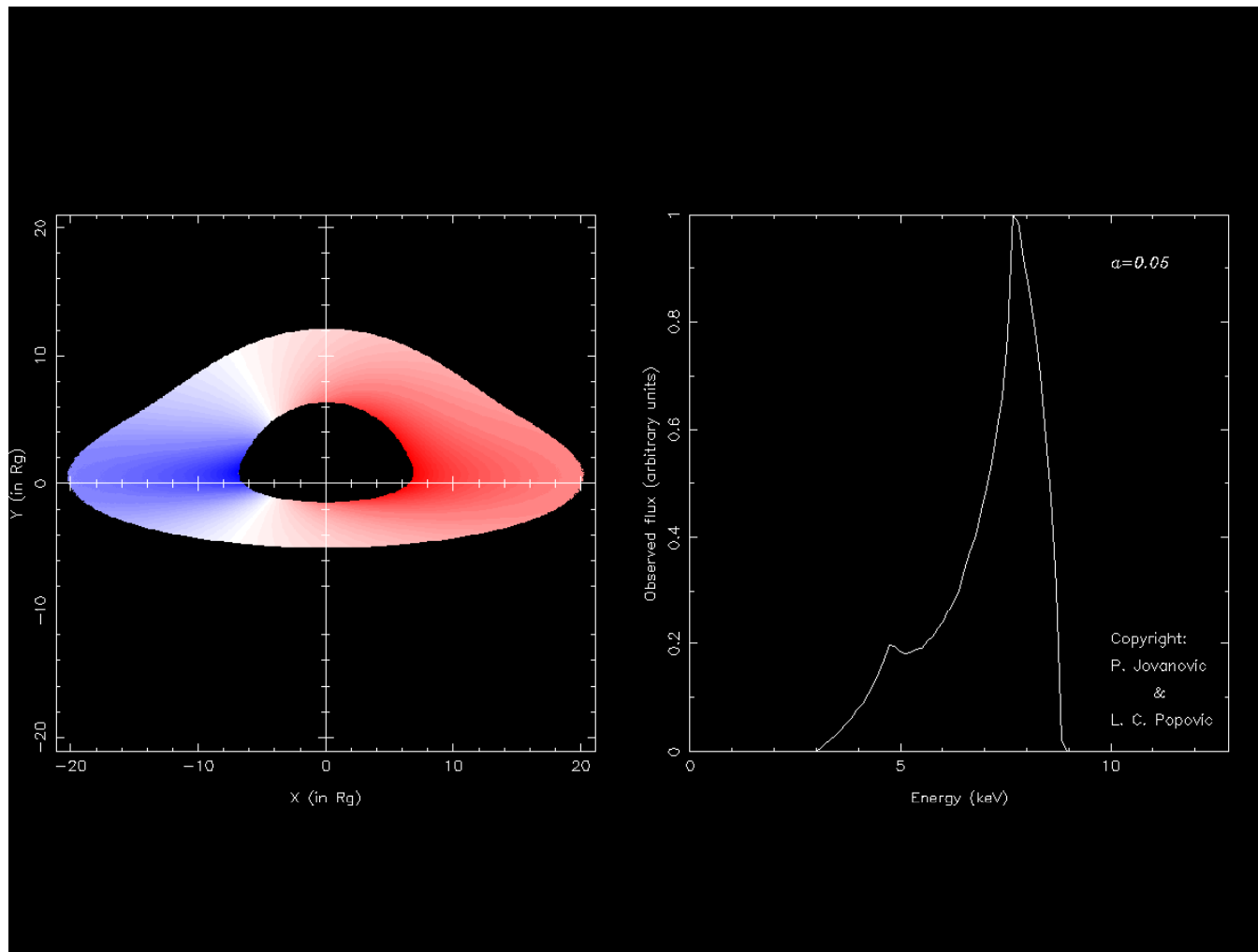


# Our recent investigations and results

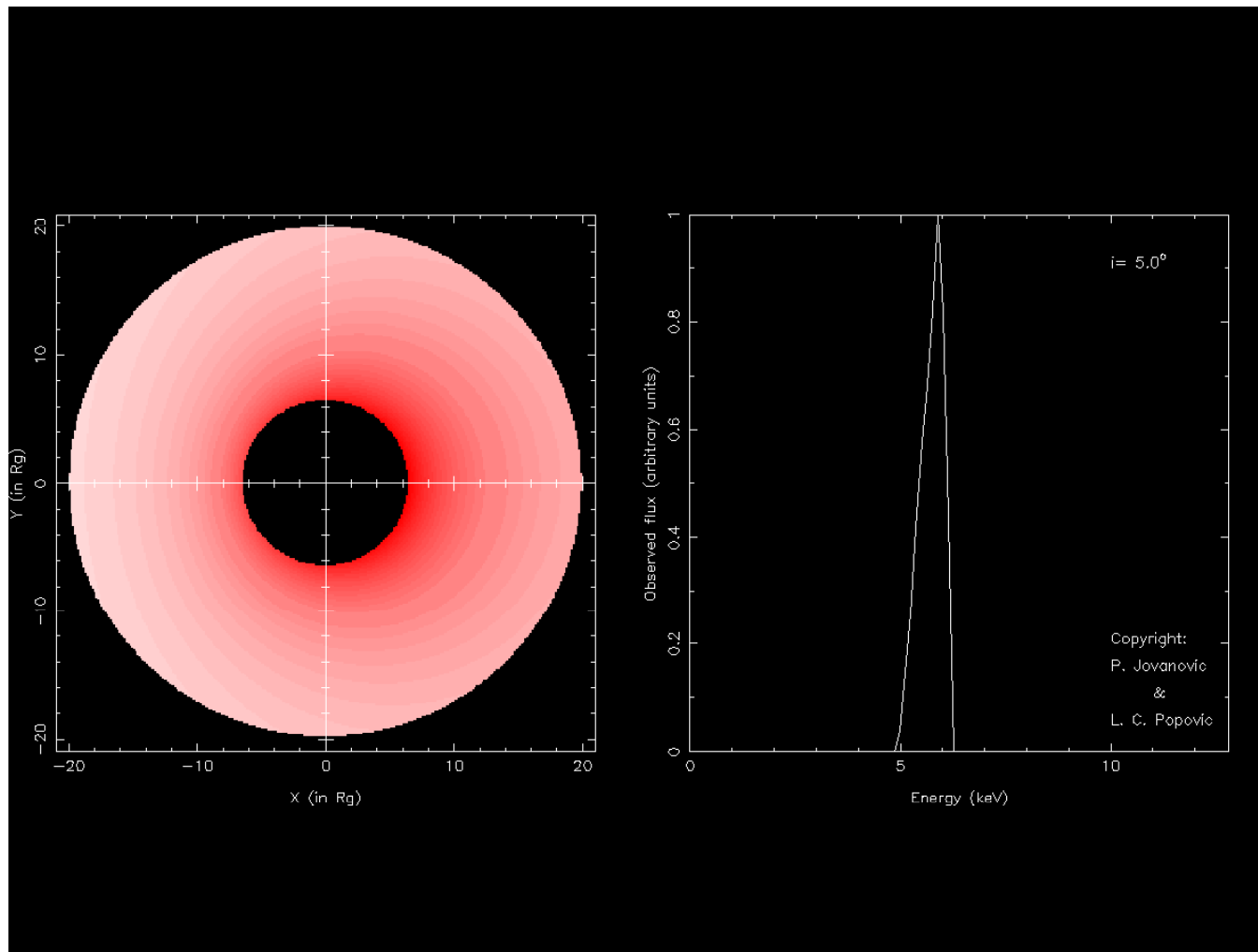
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1. Modeling of emission of accretion disk around supermassive BH using numerical simulations based on a ray-tracing method
2. Investigation of the effects of strong gravitational field by comparison between modeled and observed iron  $K\alpha$  line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

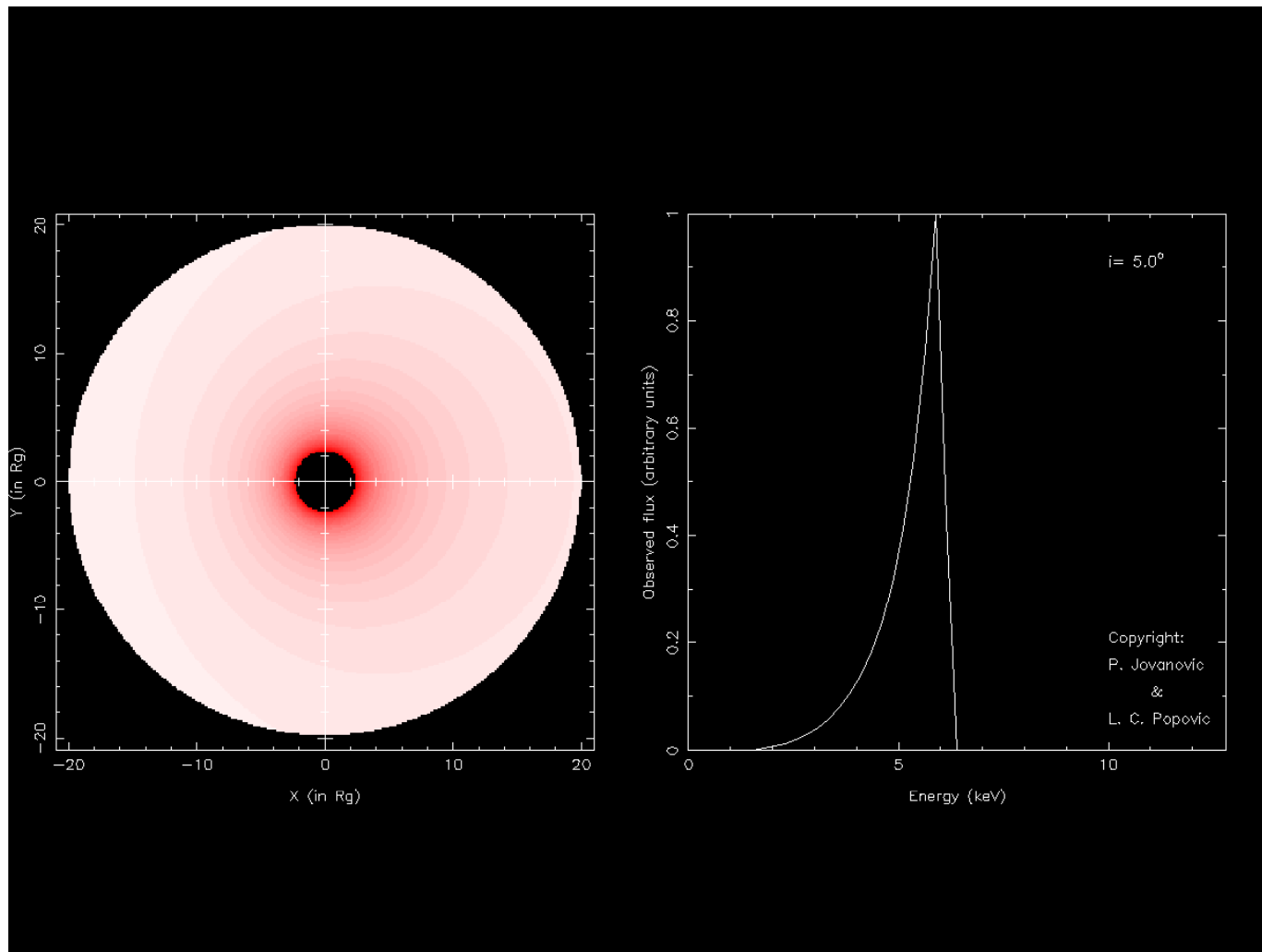
Numerical simulations of a highly inclined accretion disk ( $i=75^\circ$ ) for different values of angular momentum parameter  $a$  (left) and the corresponding profiles of the Fe  $K\alpha$  line (right)

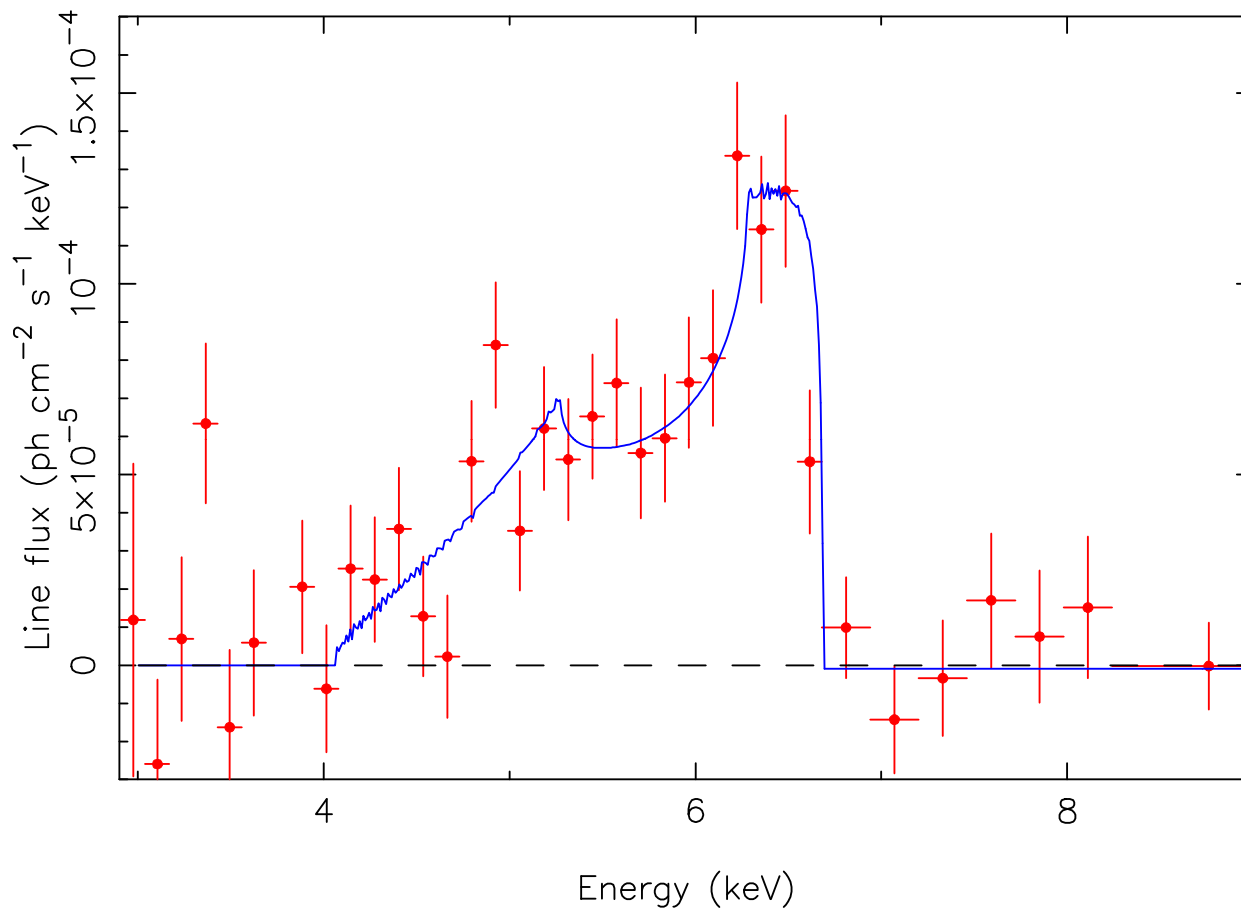


Numerical simulations of an accretion disk in Schwarzschild metric for different inclination angles  $i$  (left) and the corresponding profiles of the Fe  $K\alpha$  line (right)



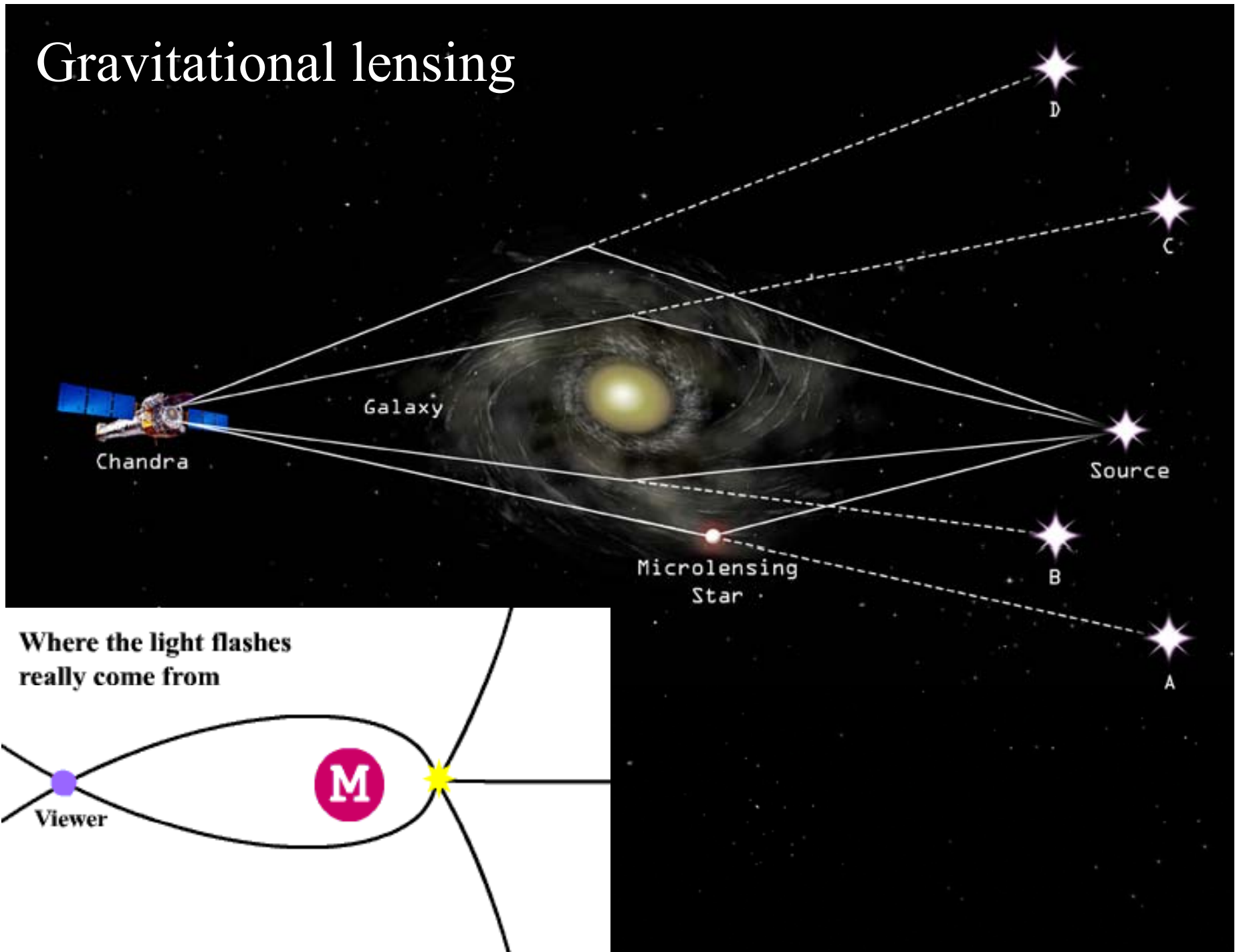
Numerical simulations of an accretion disk in Kerr metric with angular momentum parameter  $a = 0.998$  for different inclination angles  $i$  (left) and the corresponding profiles of the Fe  $K\alpha$  line (right)





The Fe K $\alpha$  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

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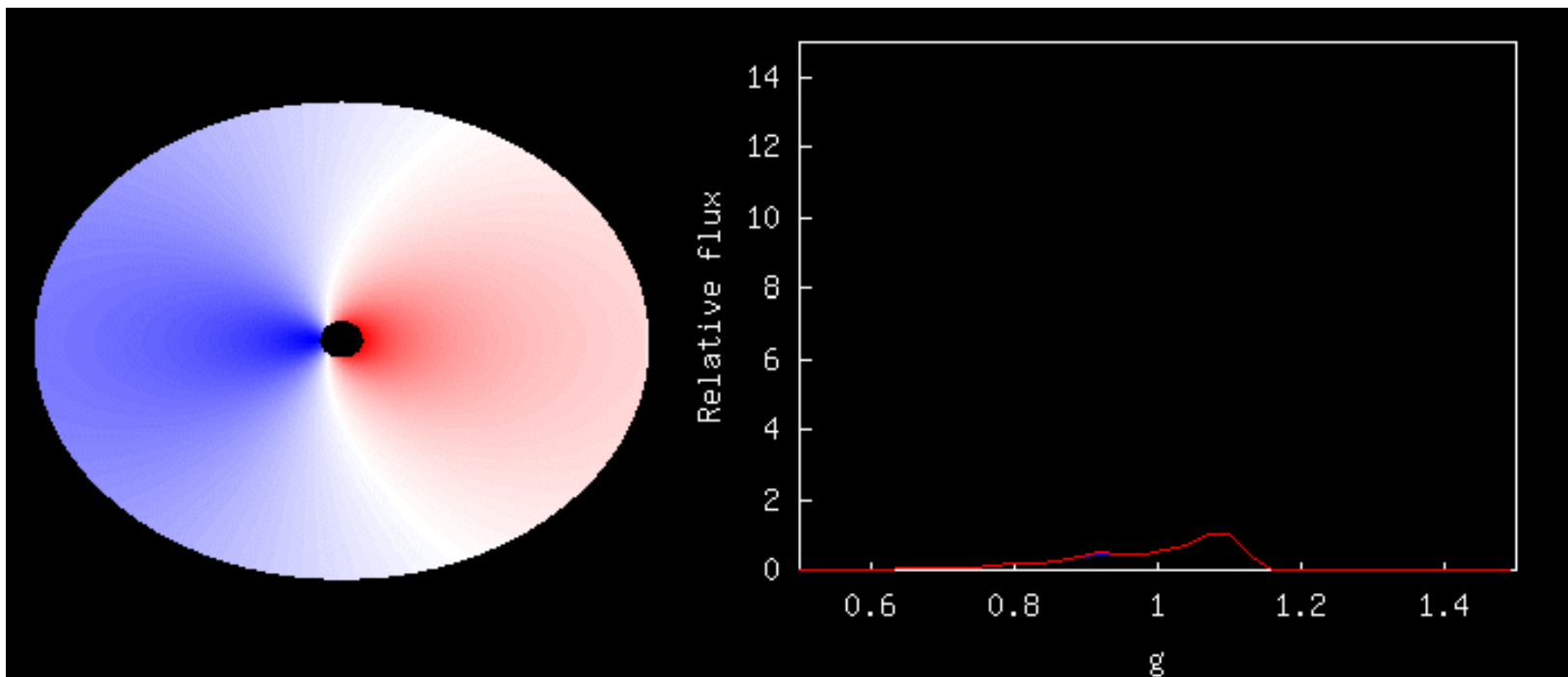
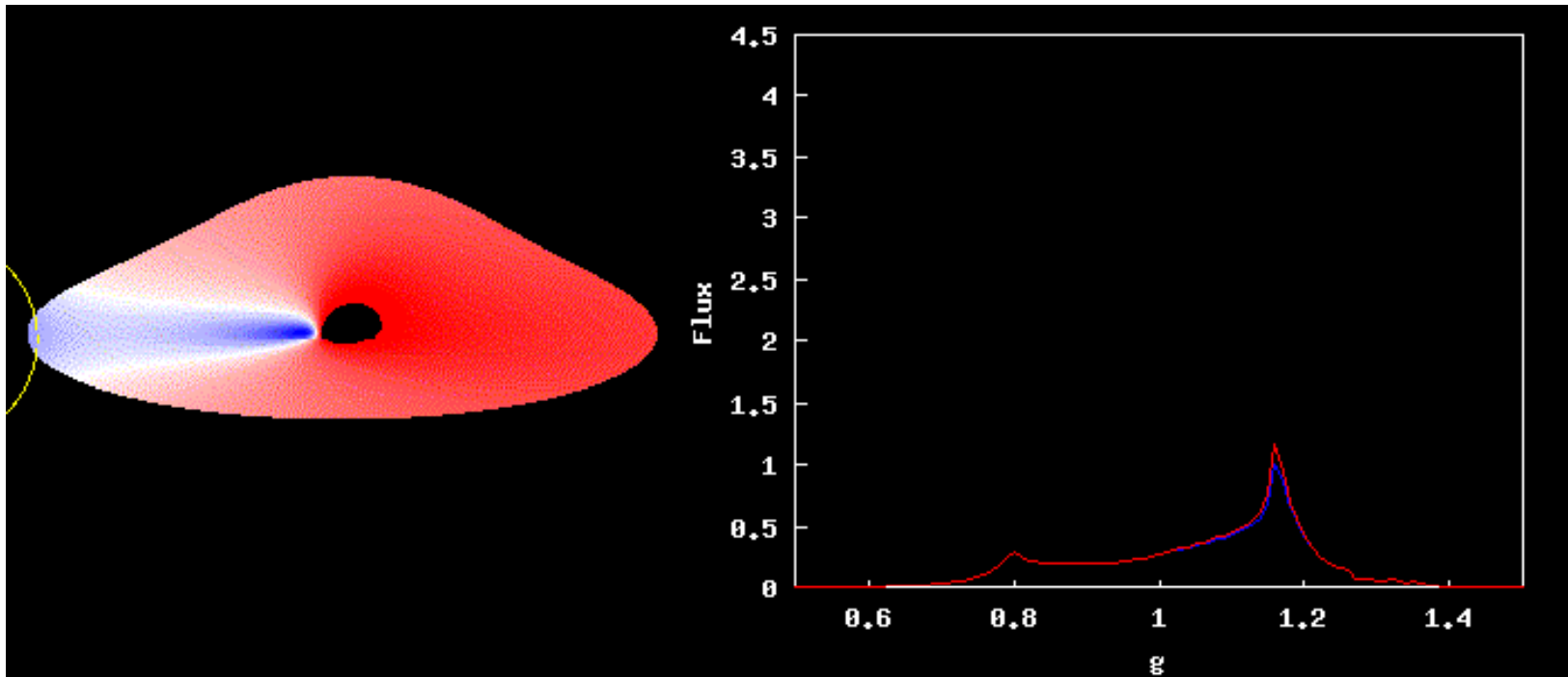
amplification of a point-like microlens: 
$$A(X, Y) = \frac{u^2(X, Y) + 2}{u(X, Y) \sqrt{u^2(X, Y) + 4}}$$

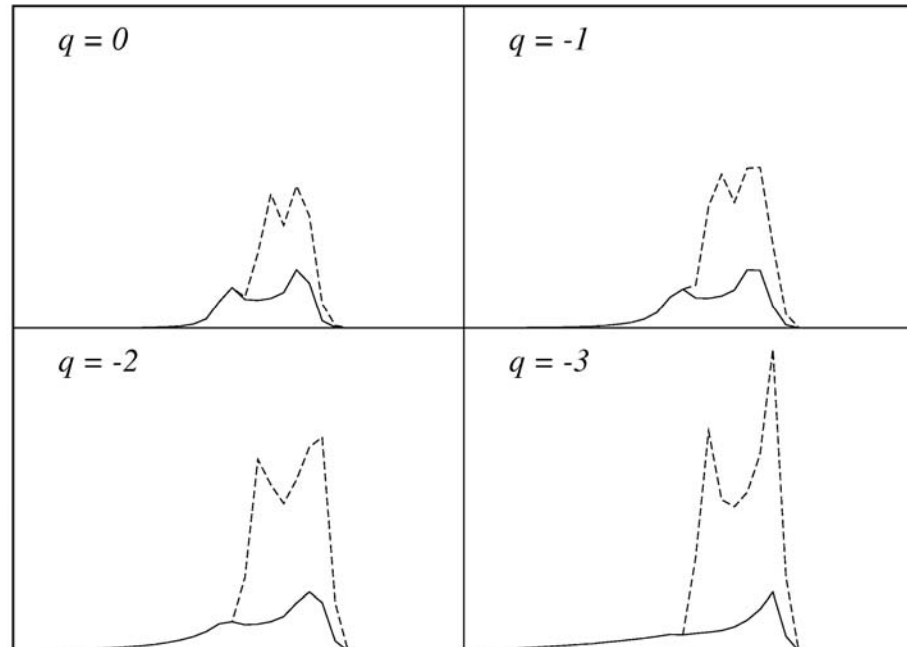
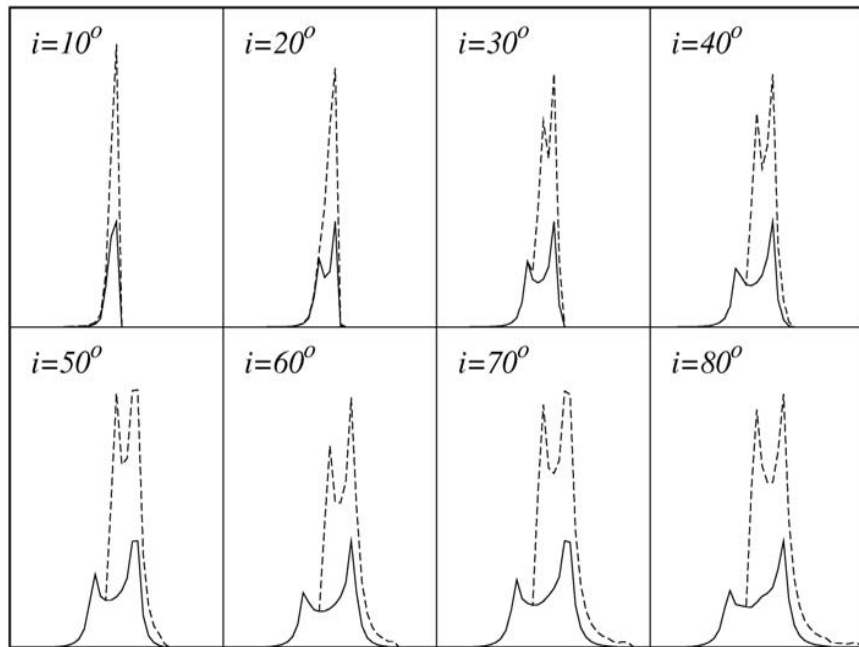
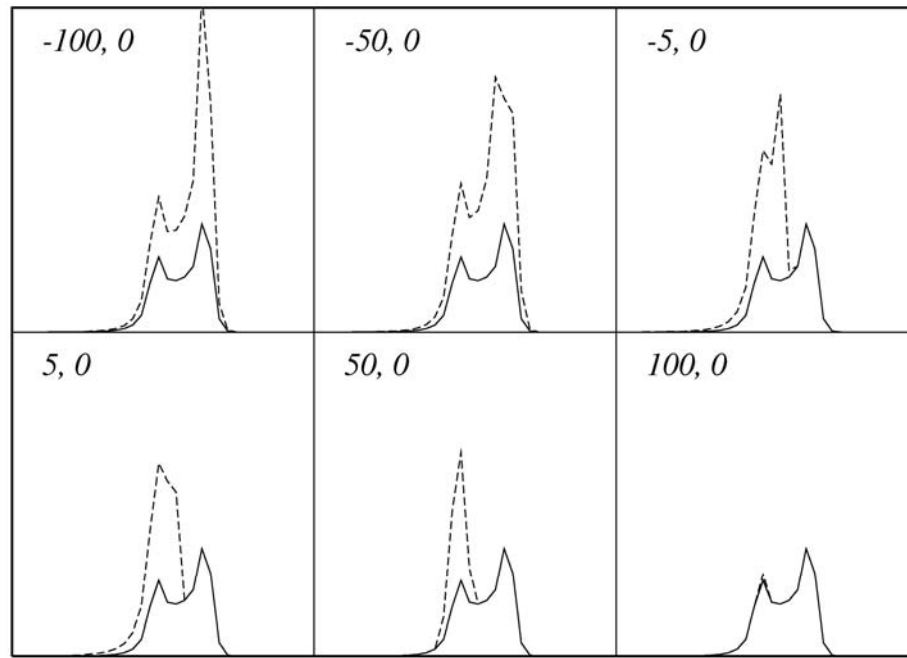
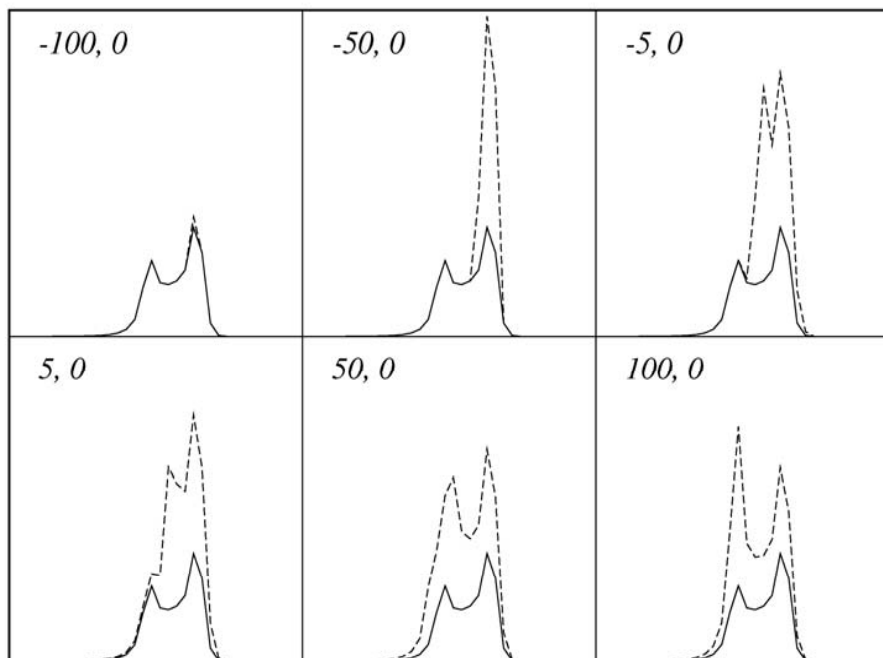
amplification of a caustic microlens: 
$$A(X, Y) = A_0 + \frac{K}{\sqrt{\kappa(\xi - \xi_c)}} \cdot H(\kappa(\xi - \xi_c))$$

amplified brightness: 
$$I_p = \varepsilon(r)g^4(X, Y)\delta(x - g(X, Y))A(X, Y), \quad g = v_{\text{obs}}/v_0$$

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

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







# Conclusions

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- Comparisons between the modeled and observed iron  $K\alpha$  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  $K\alpha$  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

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5. A. F. Zakharov, L. Č. Popović & P. Jovanović, *Astron. Astrophys.* 420 (2004) p. 881



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**Thank you for attention!**  
THANK YOU FOR ATTENTION!