# The Fe Kα line and supermassive black holes

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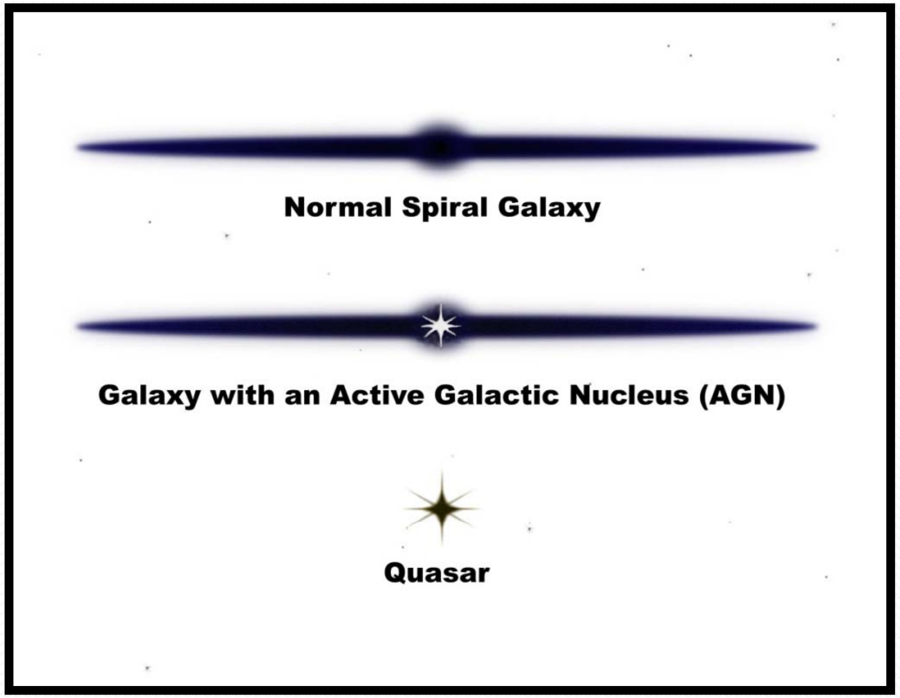
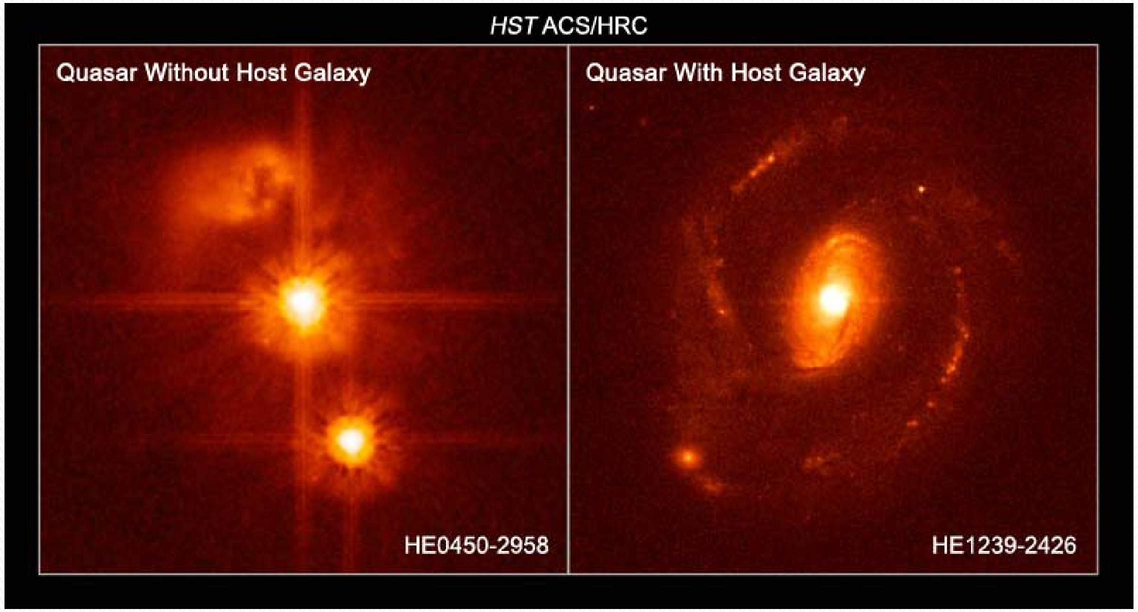
# Outline

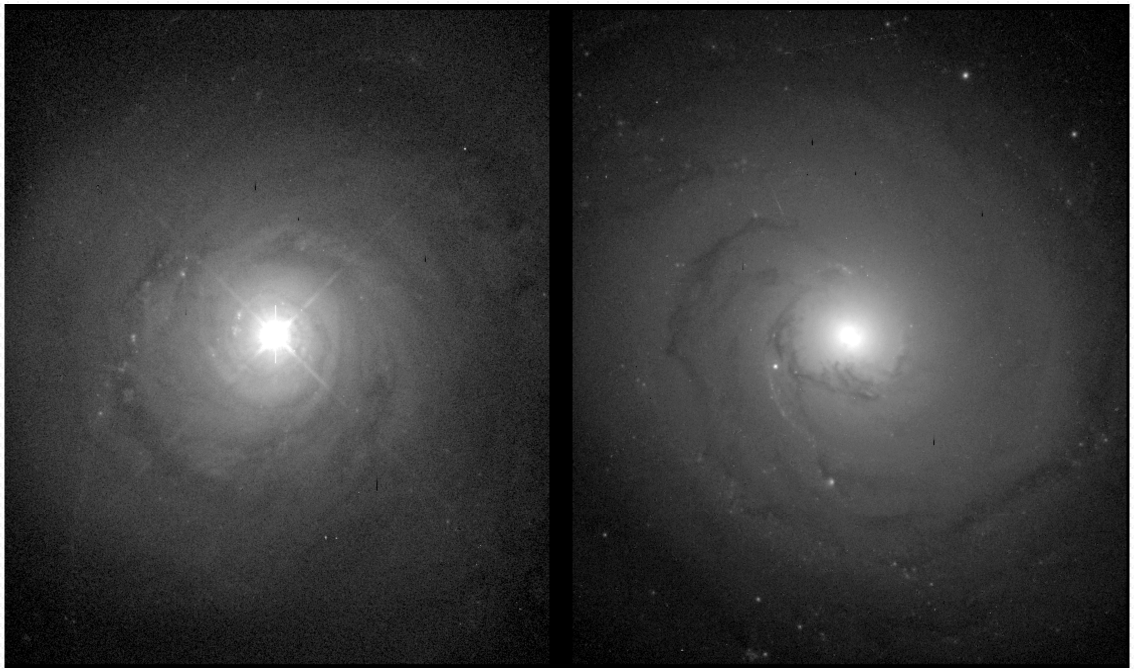
- Active Galactic Nuclei (AGN)
- Supermassive Black Holes (SMBH)
- Fe Kα spectral line
- Our investigations and results
- Conclusions
- References

# Active Galaxies and Quasars

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

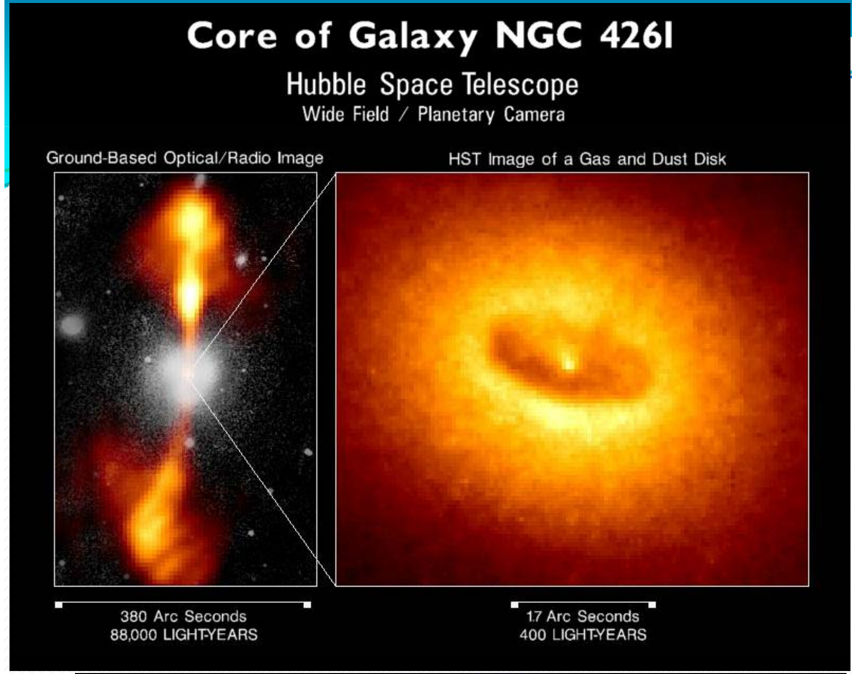


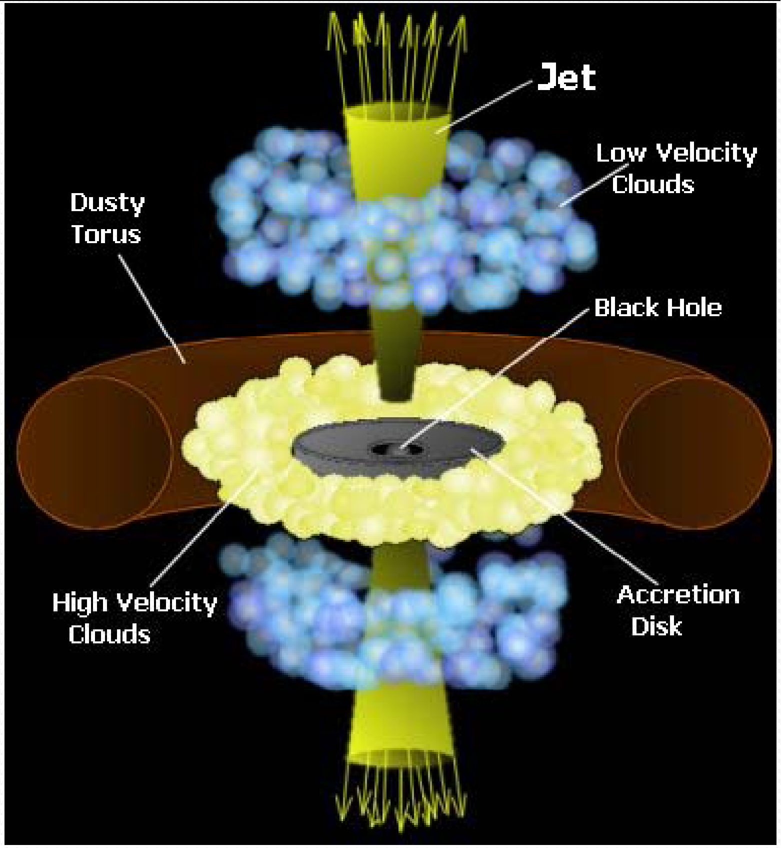



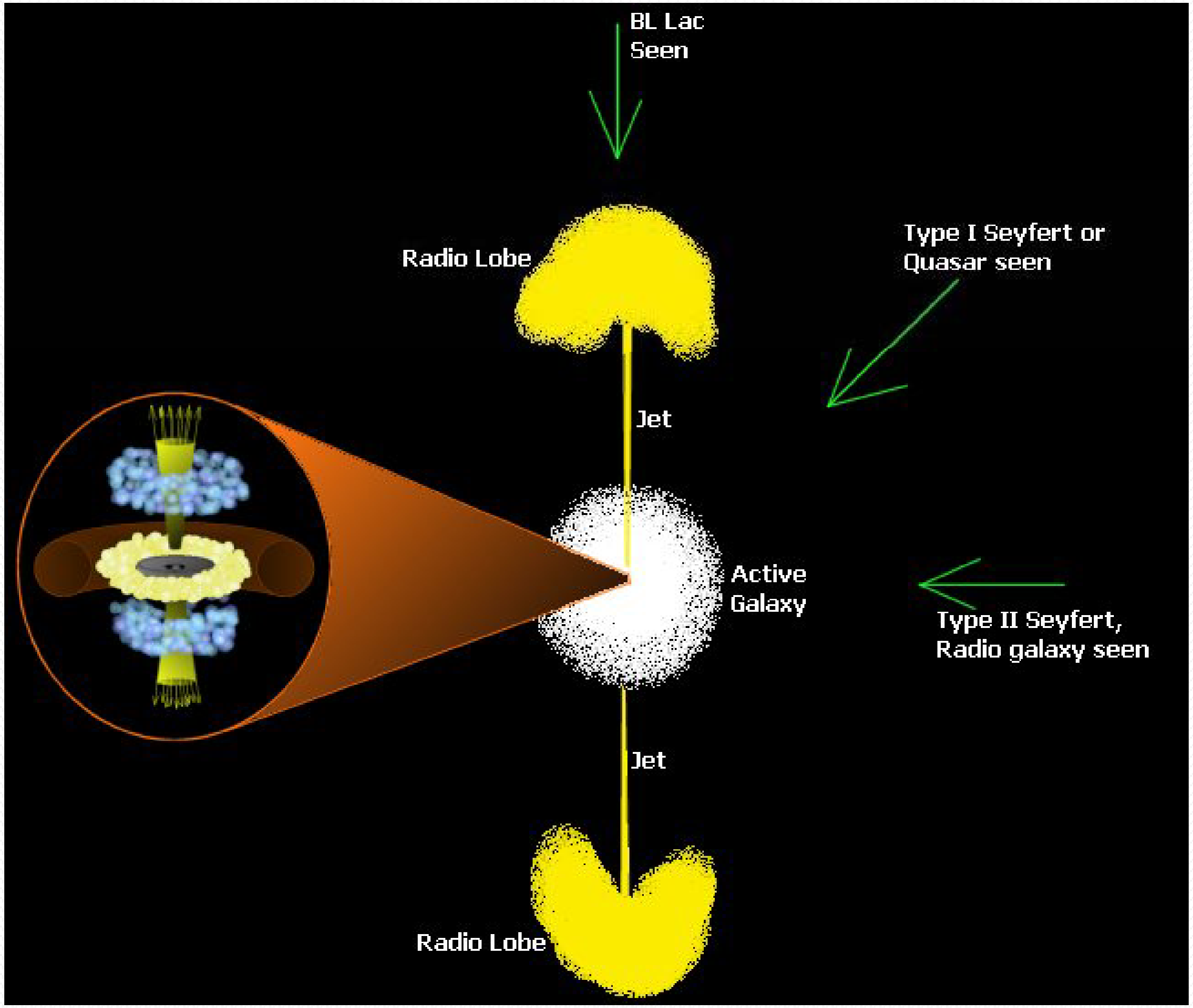



Left: NGC 5548 (Seyfert galalaxy)
Right: NGC 3277 (regular galaxy)

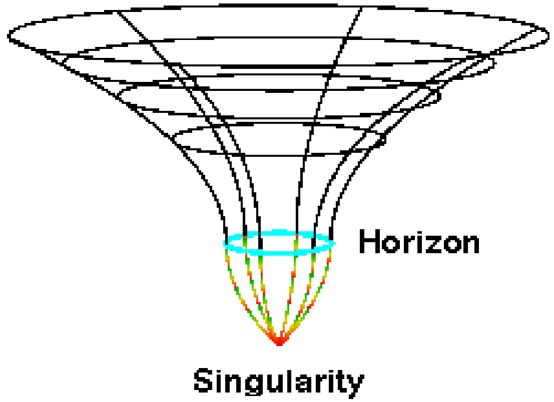
# Unified model of AGN



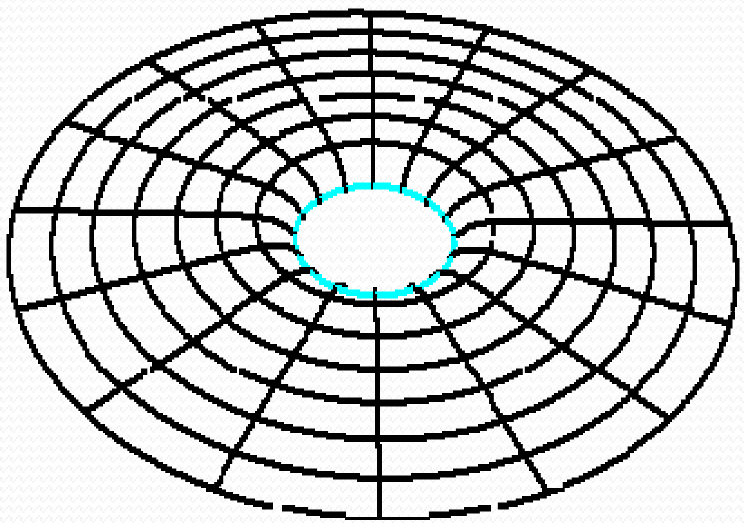
# Space-time geometry in Vicinity of Supermassive BH




## 1. Schwarzschild metric – nonrotating BH

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

- Schwarzschild radius: $R_S = \frac{2GM}{c^2}$
- gravitational radius: $R_g = \frac{R_S}{2} = \frac{GM}{c^2}$



$G$ – Newton's gravitational constant

$c$ – speed of light, $M$ – mass of BH

## 2. Kerr metric – rotating BH

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

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

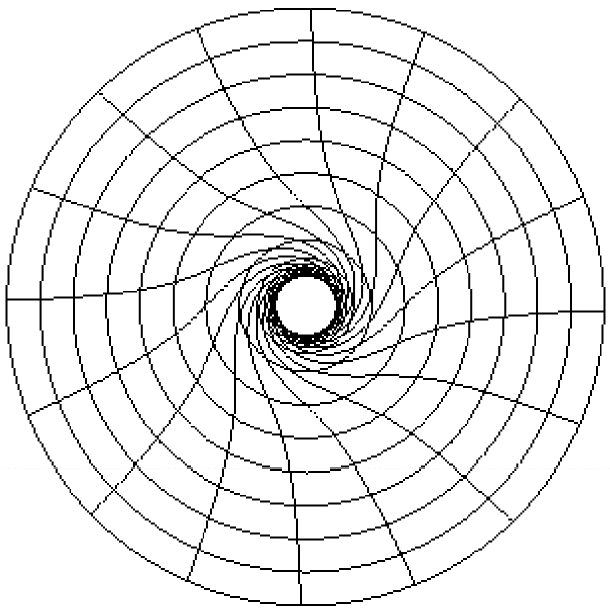
$$\Sigma = r^2 + a^2\cos^2\theta, \quad \Delta = r^2 + a^2 - 2Mr, \quad A = (r^2 + a^2)^2 - a^2\Delta\sin^2\theta$$

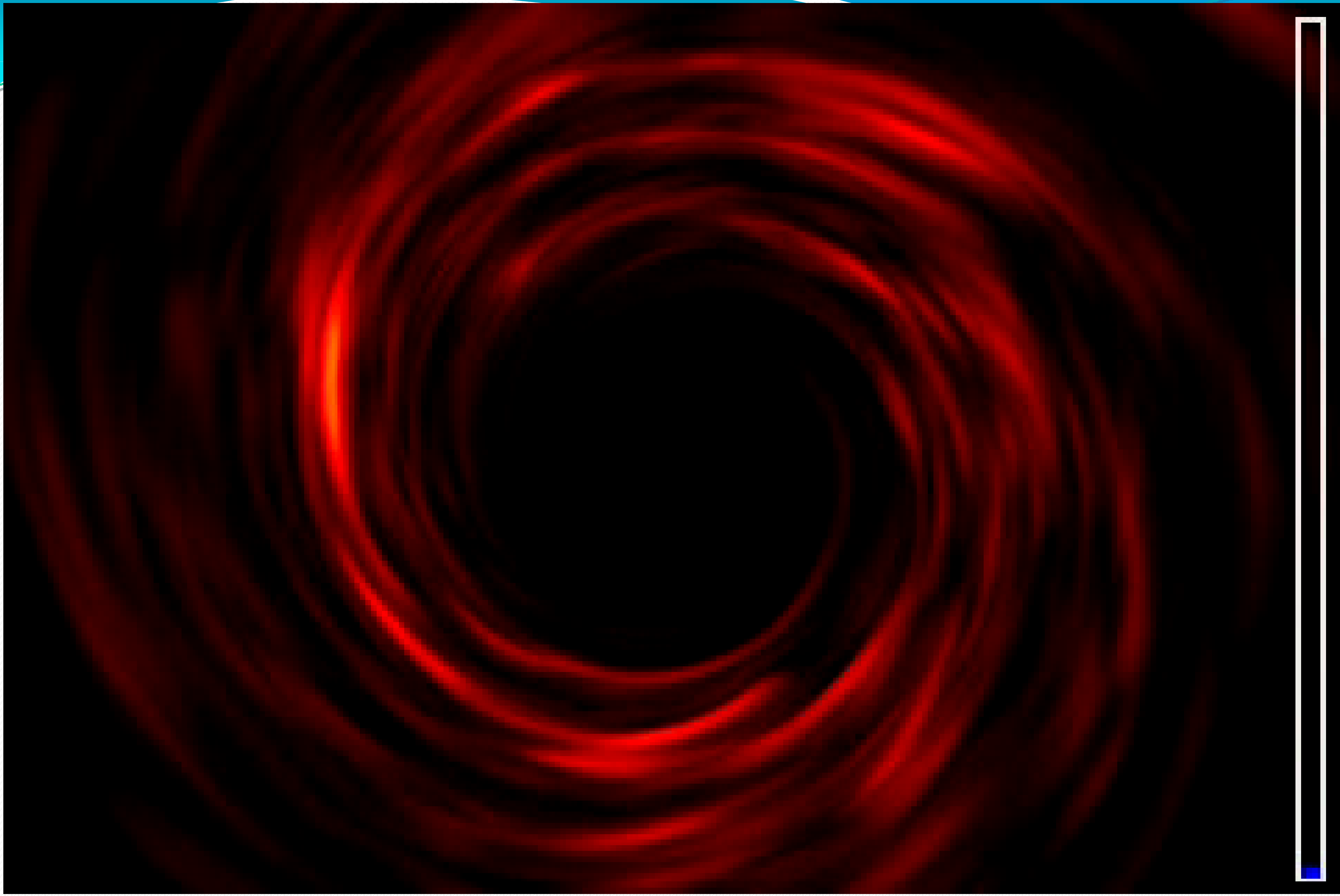
- horizon of BH: $\Delta = 0 \Rightarrow r_h = M + \sqrt{M^2 - a^2}$

- radius of marginally stable orbit:

$$r^2 - 6Mr \mp 8a\sqrt{Mr} - 3a^2 = 0 \Rightarrow$$

$$\Rightarrow R_{ms} = \begin{cases} 6M, & a = 0 \\ M, & a = M \end{cases}$$





Armitage, P. J., Reynolds, C. S. 2003, *MNRAS*, 341, 1041

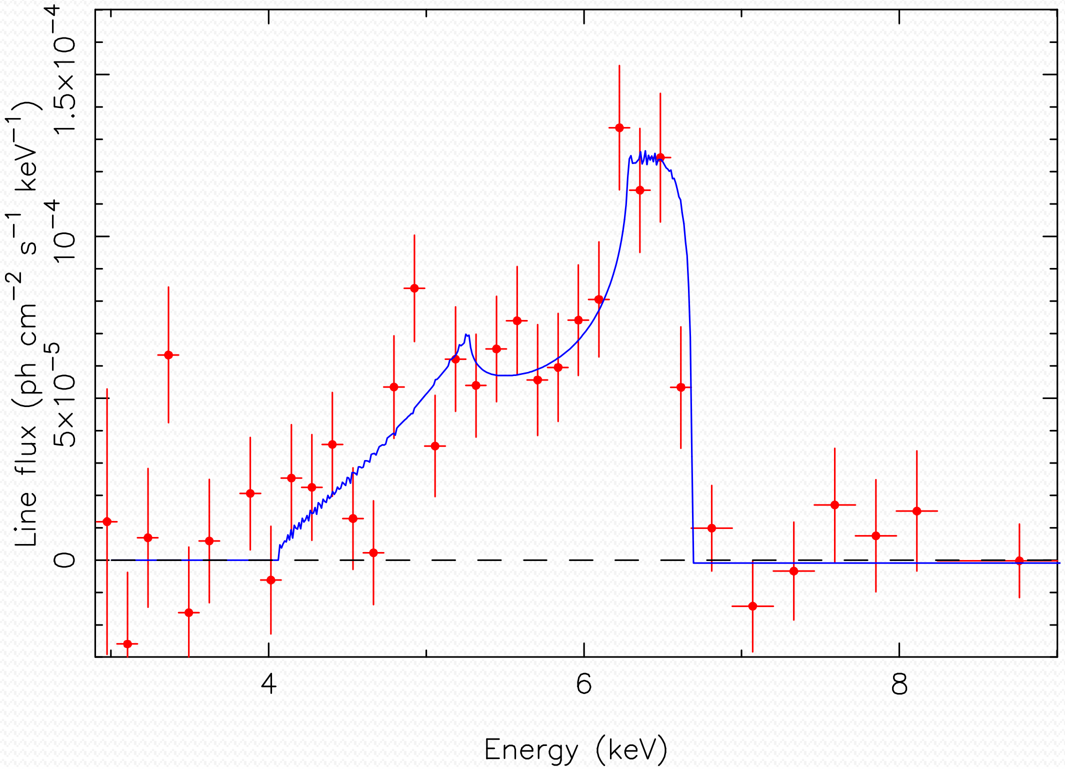
# Fe Kα spectral line

- broad emission line at 6.4 keV
- asymetric profile with narrow bright **blue** peak and wide faint **red** peak
- Line width corresponds to velocity:

  v ~ 100.000 km/s (MCG-6-30-15)

  v ~ 48.000 km/s (MCG-5-23-16)

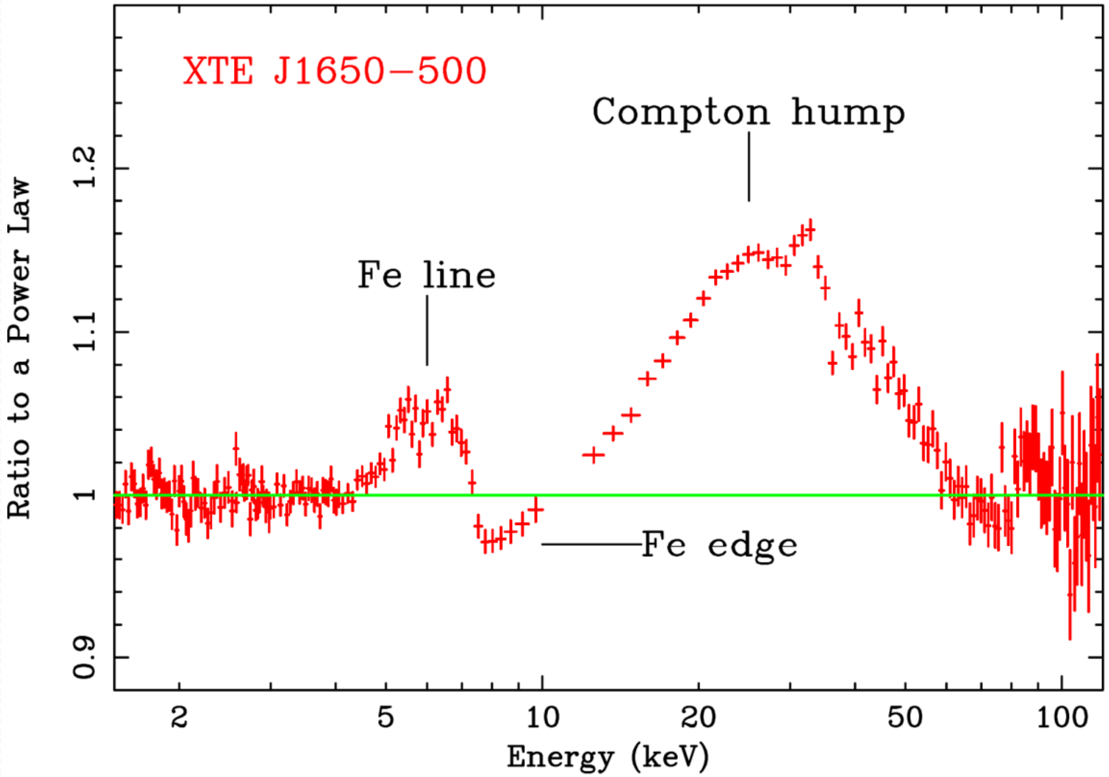
  v ~ 20.000 – 30.000 km/s (other AGN)
- variability of both: line shape and intensity
- Importance:
  1. Studying accretion disk emission close to SMBH
  2. probing strong gravity effects and testing GR predictions
  3. determining SMBH properties



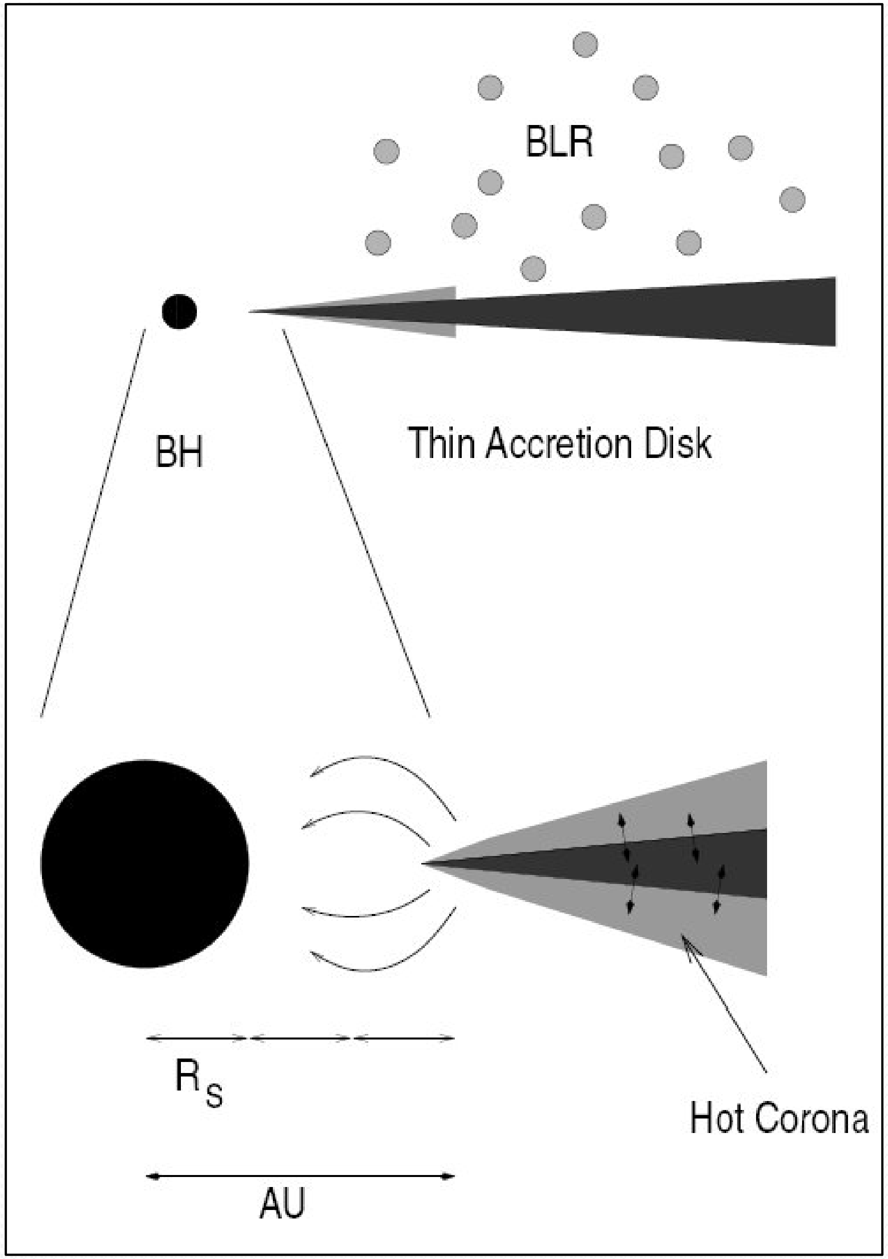

The Fe Kα line profile from Seyfert I galaxy MCG-6-30-15 observed by the ASCA (Tanaka, Y. et al, 1995, *Nature*, **375**, 659) and the modeled profile expected from an accretion disk around a Schwarzschild BH.

# Production of Fe Kα: thin disk + hot corona

- Hard X-ray (power-law) continuum illuminates accretion disk
- Photoelectric absorption of hard X-ray photons followed by fluorescent line emission at 6.4 keV
- Compton reflection hump at 30 keV



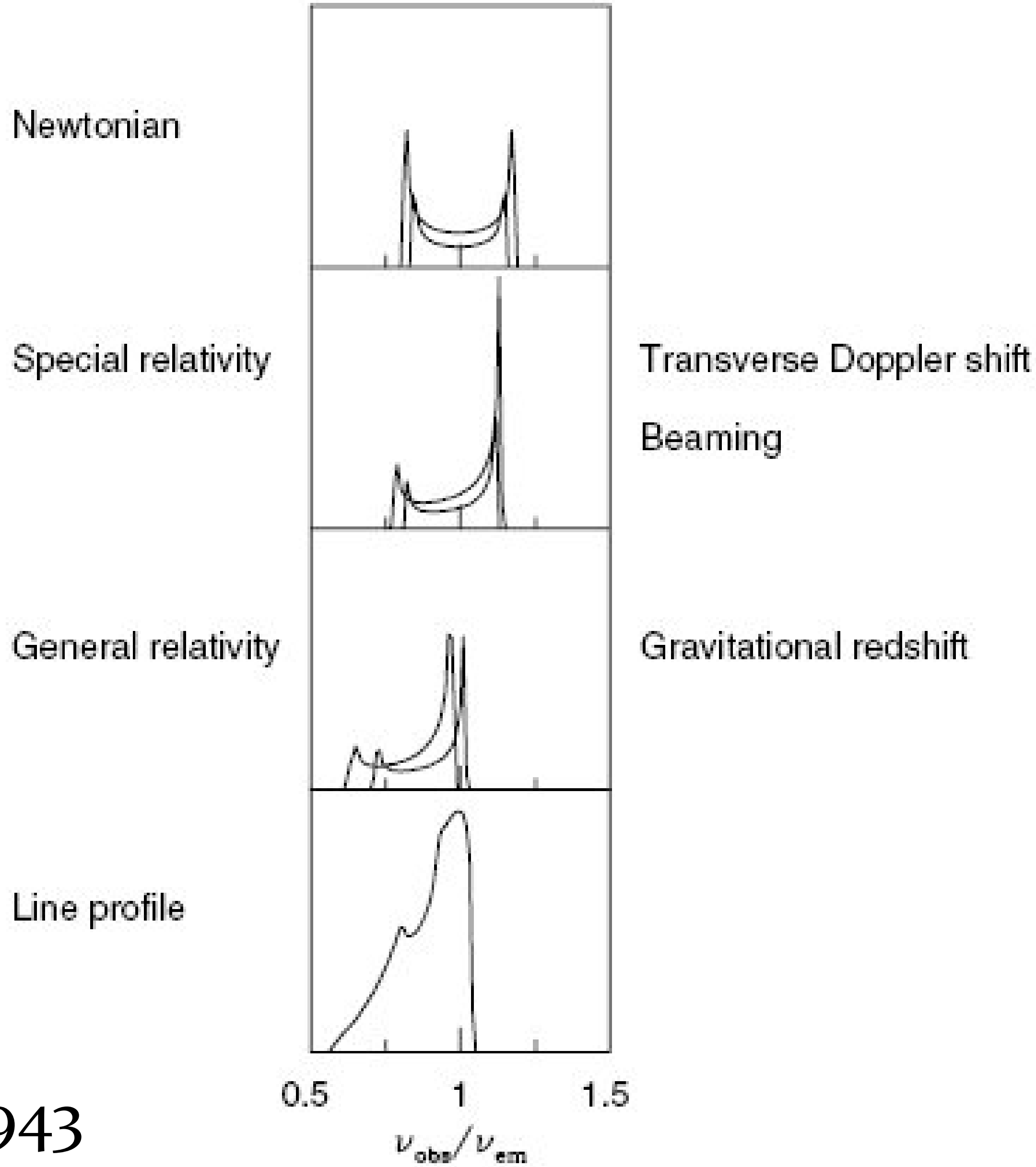

Fabian, A. C. 2006, *AN*, 327, 943




Wilms et al. 2004, *MemSAI*, 75, 519

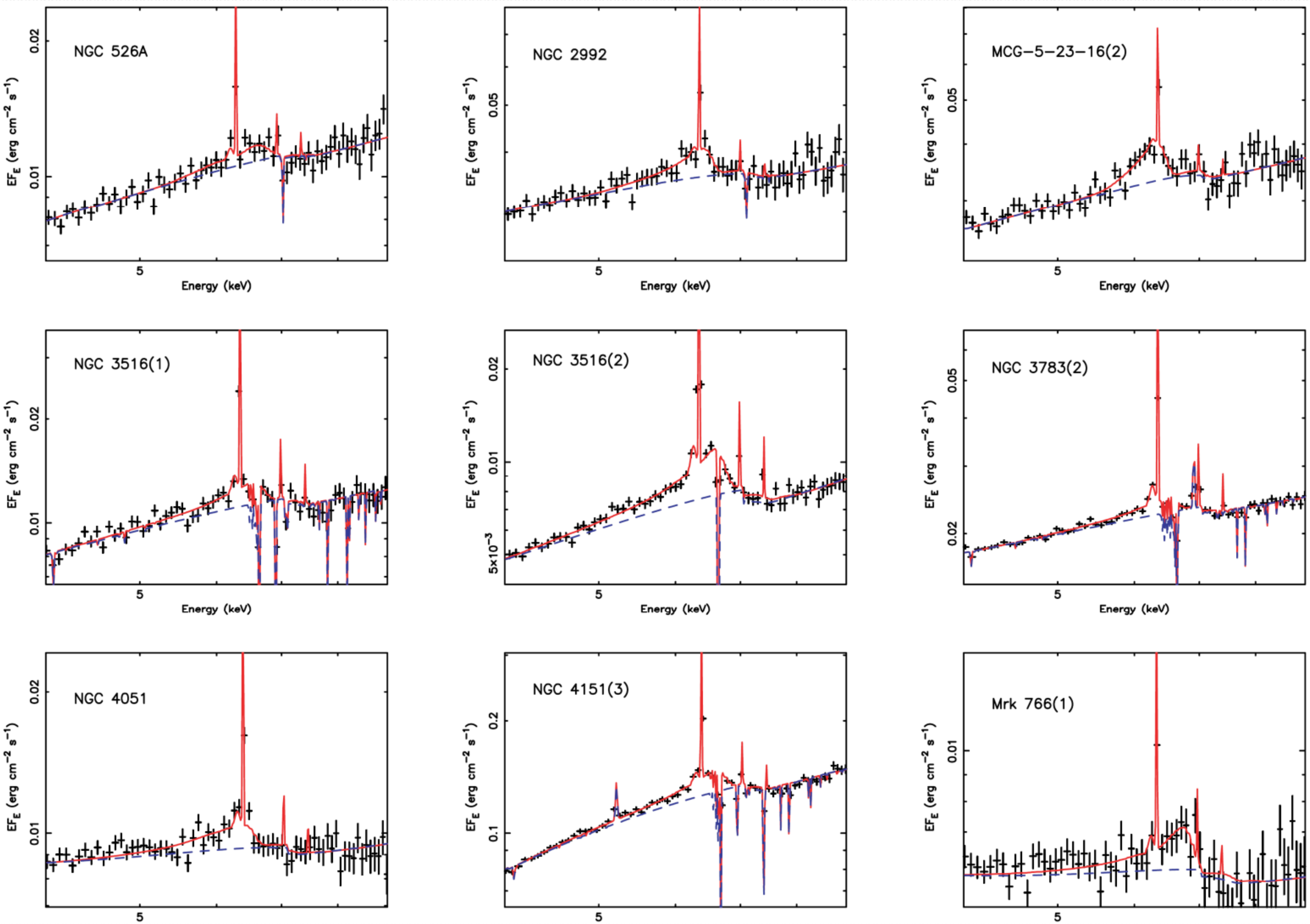
# Relativistic effects on Fe Kα line

- Doppler shift: symmetric, double-peaked profile
- Relativistic beaming: enhance blue peak relative to red peak
- Gravitational redshift: smearing blue emission into red



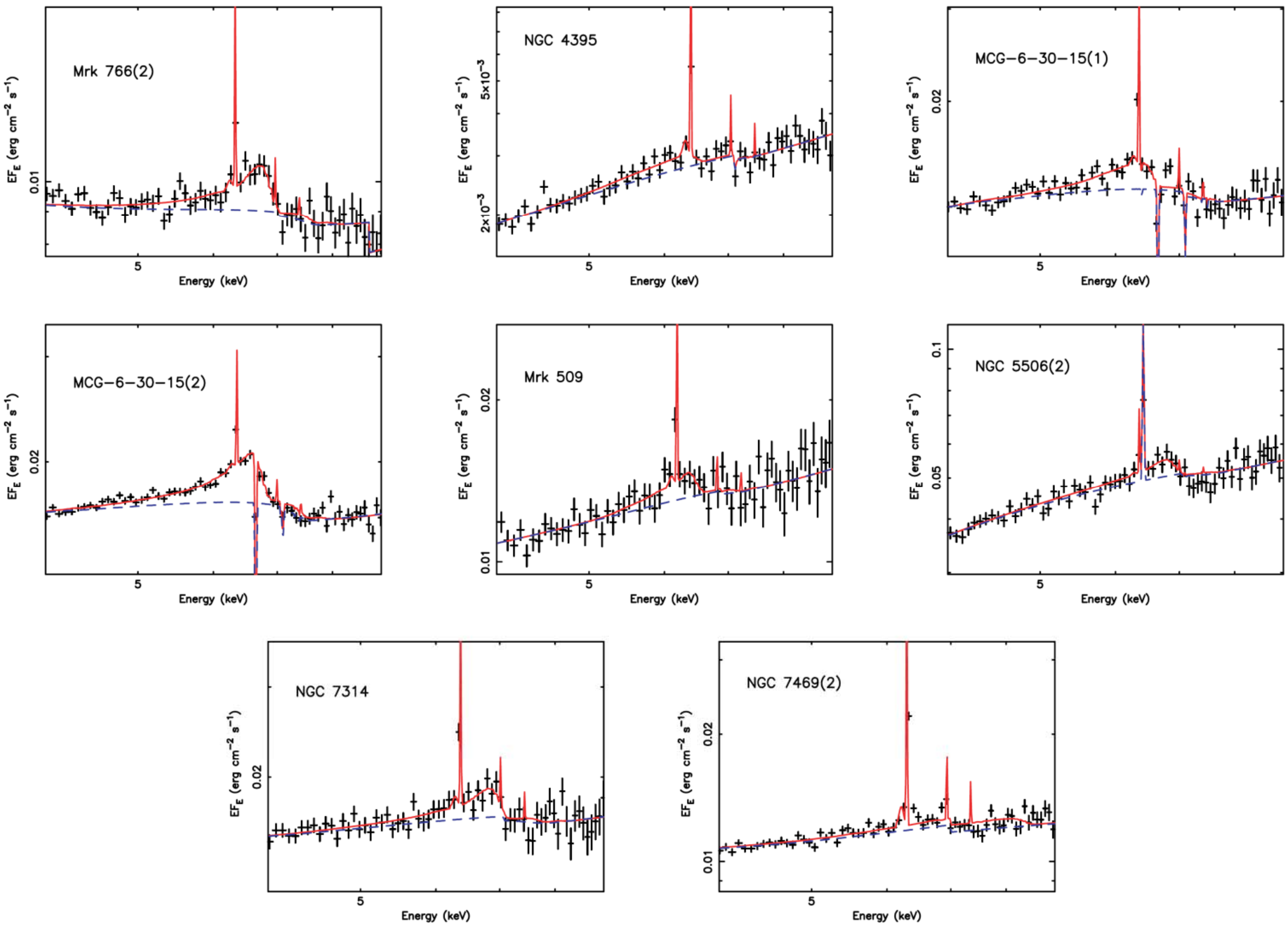

Fabian, A. C. 2006, *AN*, 327, 943

# Some observed Fe Kα line profiles I



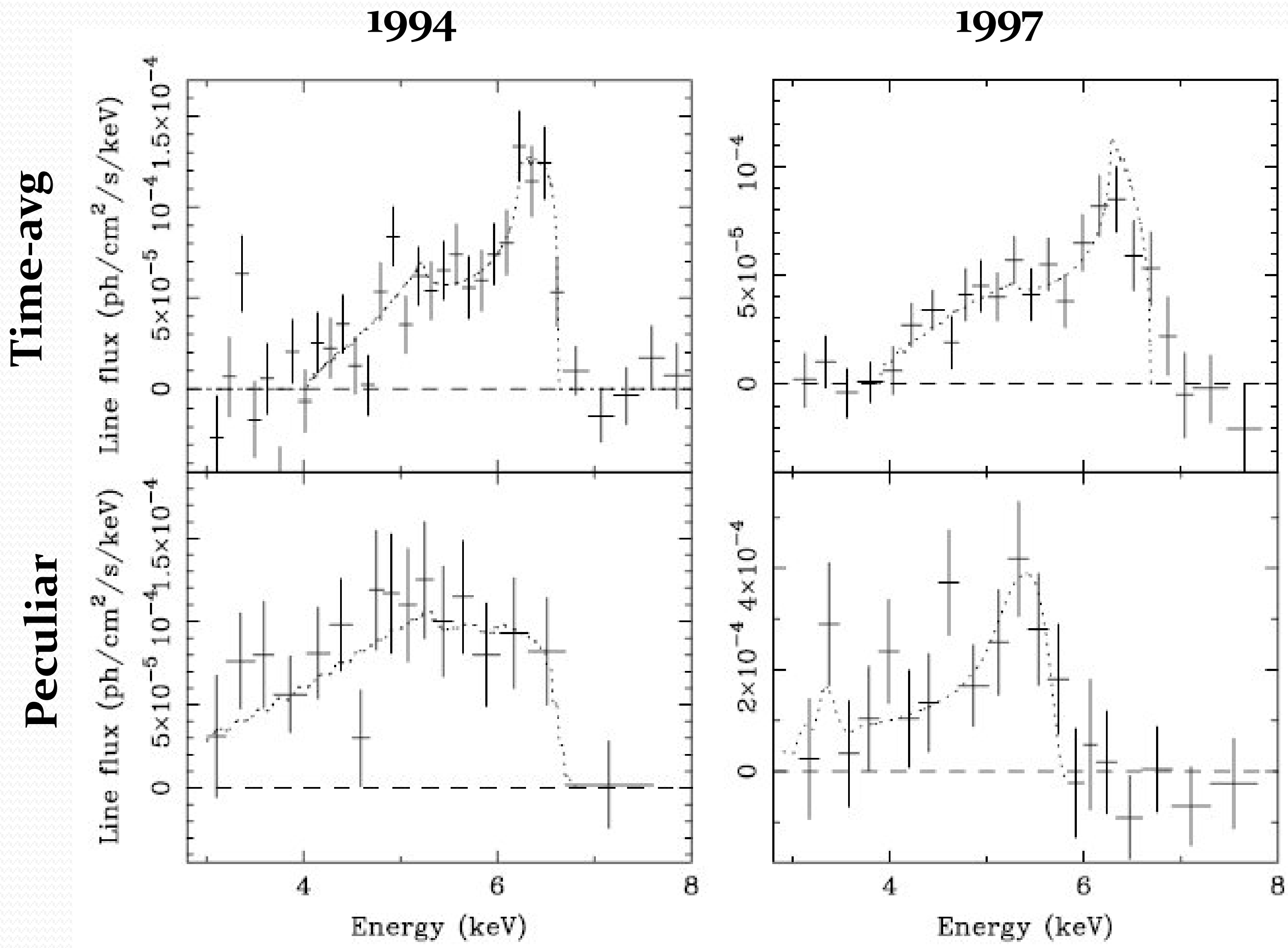

Nandra et al, 2007, *MNRAS,* **382**, 194

# Some observed Fe Kα line profiles II




Nandra et al, 2007, *MNRAS*, **382**, 194

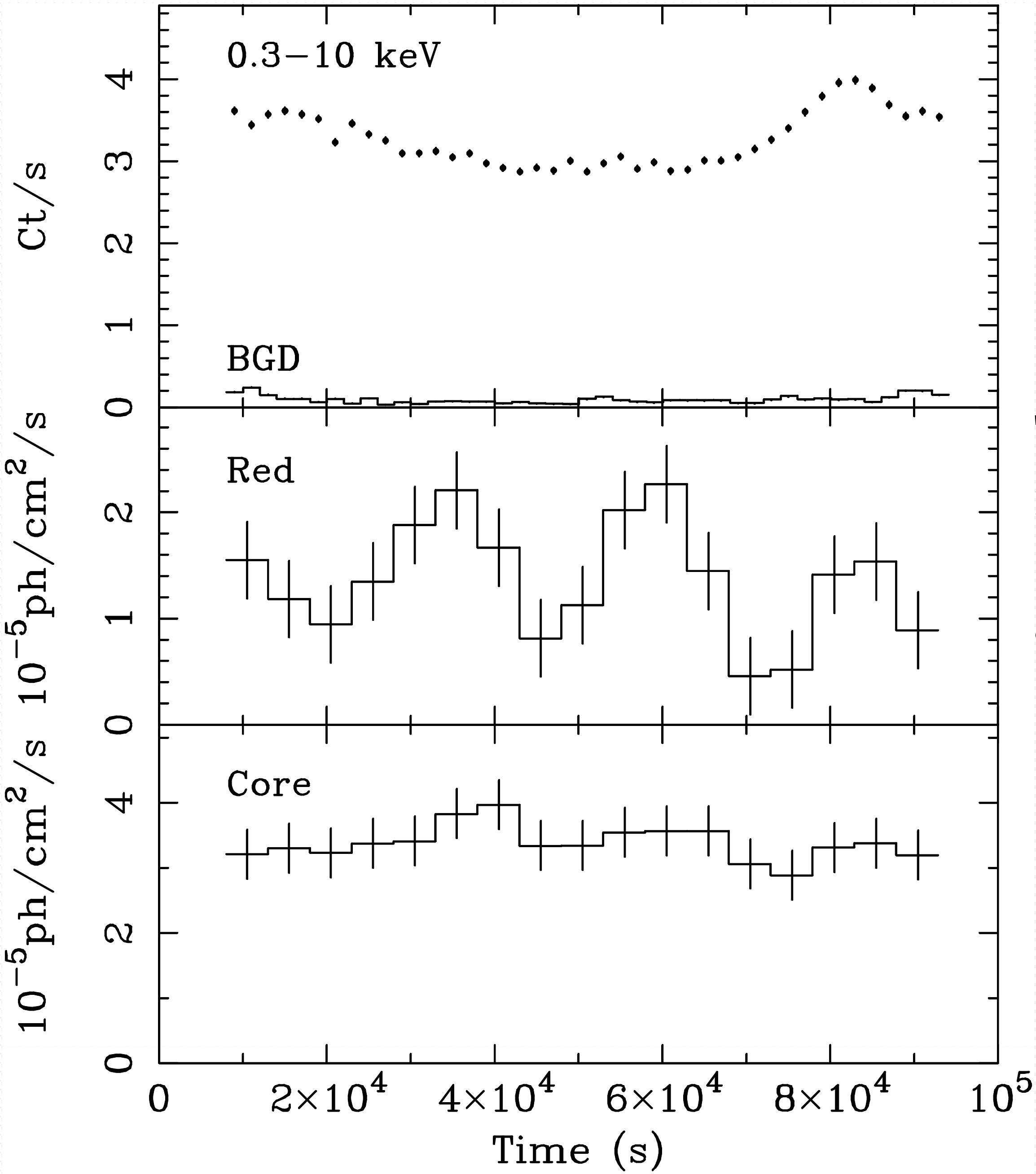
# Observed variability of the Fe Kα line shape: MCG-6-30-15




- Both peculiar line shapes can be explained by large gravitational redshift in small radii on the accretion disk

Reynolds, C. S., Nowak, M. A. 2003, *Physics Reports*, 377, 389

# Observed light curves of the Fe Kα line




The light curves of the 0.3-10 keV flux of NGC 3516 (top), the Fe Kα 5.8-6.2 keV "red" feature (middle), and the 6.4 keV line core (bottom), observed by XMM-Newton

Iwasawa, Miniutti & Fabian, 2004, *MNRAS*, **355**, 1073

# Our investigations and results

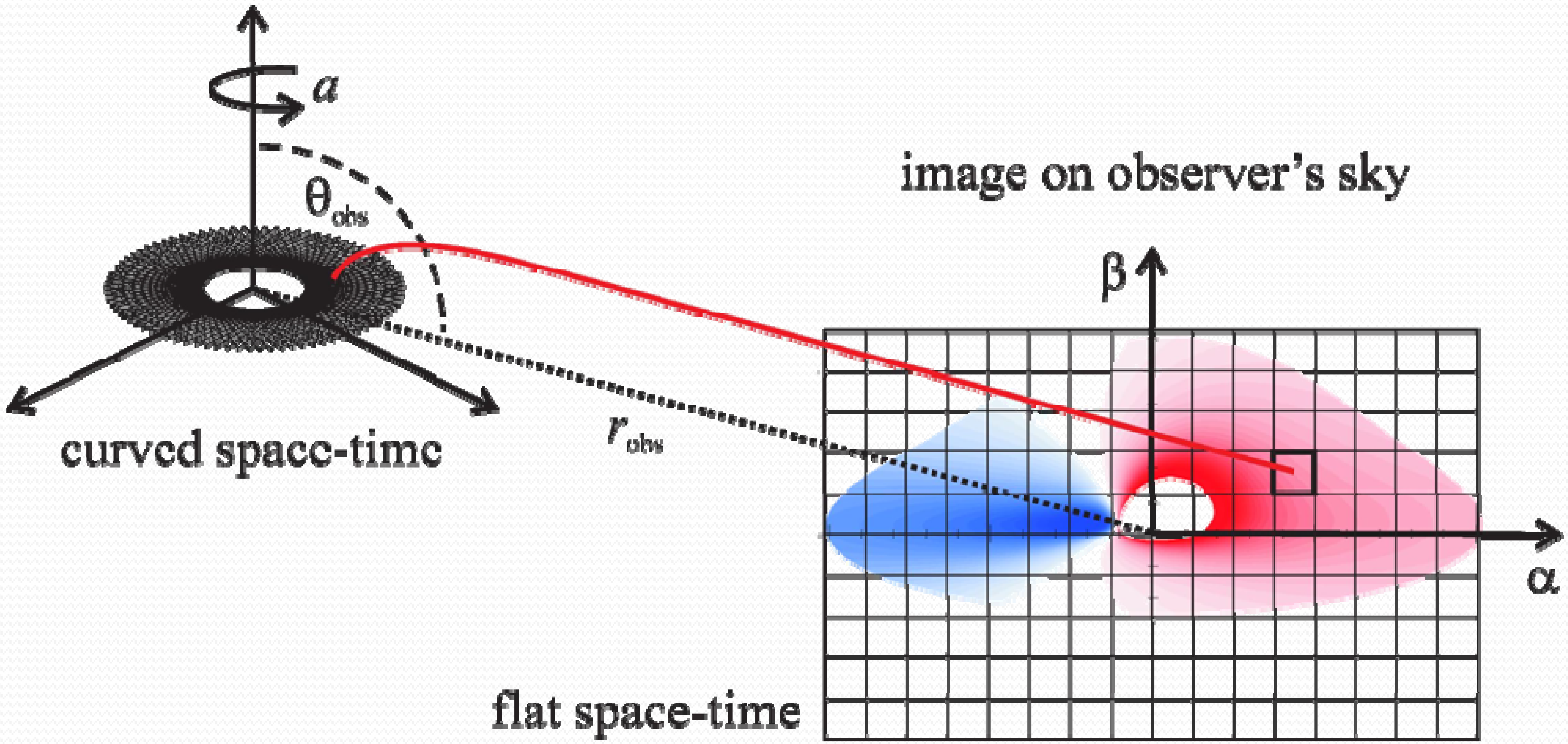
1. Modeling of emission of an accretion disk around a SMBH using numerical simulations based on a ray-tracing method in Kerr metric (first results obtained in 2001.)

2. Investigation of the effects of strong gravitational field around a SMBH

3. Studying the variability of Fe Kα line due to:
   1. internal causes:
      - disk instability and perturbations of its emissivity
   2. external causes:
      - absorption by X-ray absorbers
      - gravitational microlensing

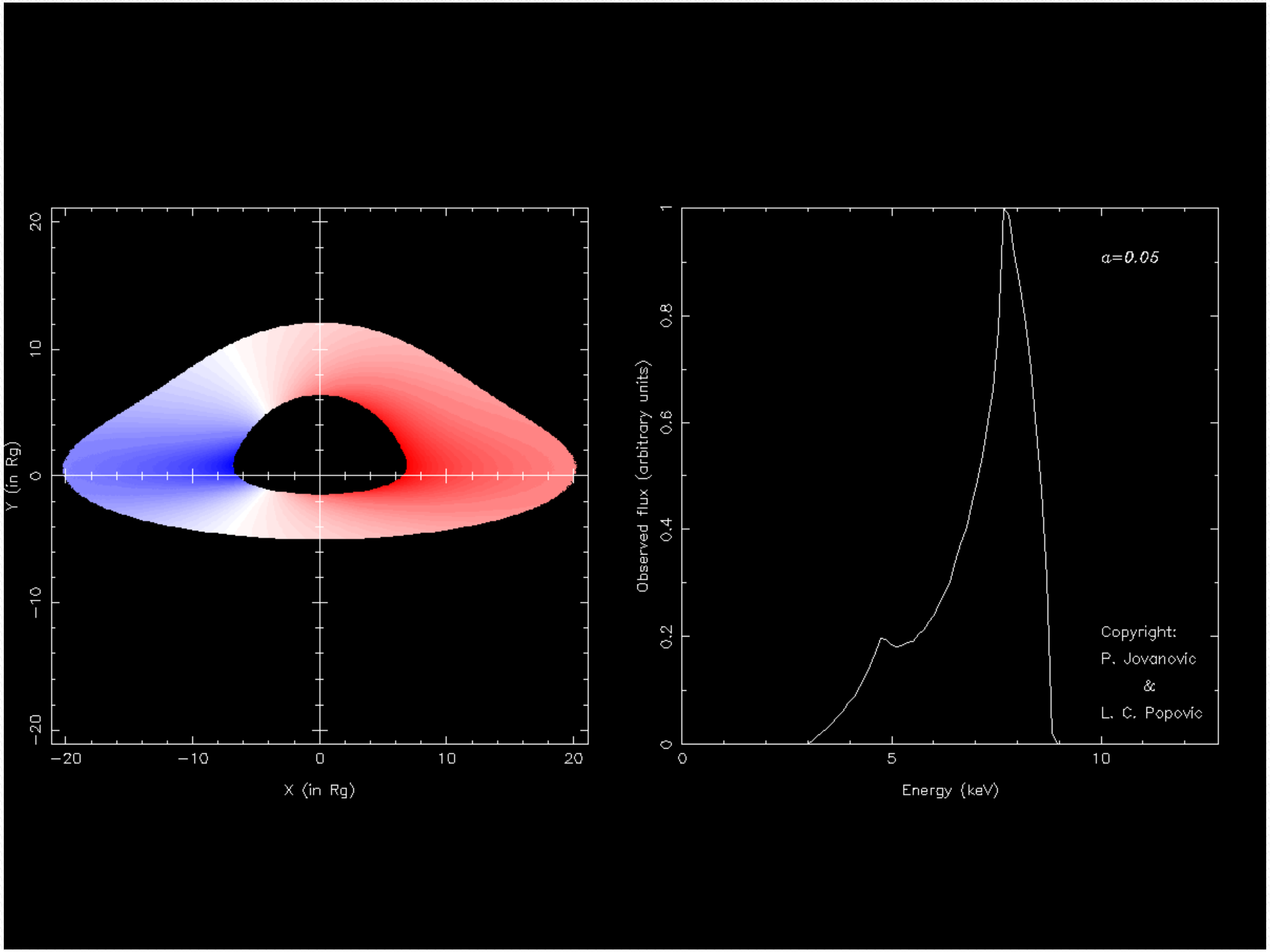
**Overview:** Jovanović P., Popović L. Č., 2009, chapter in book "*Black Holes and Galaxy Formation*", Nova Science Publishers Inc, Hauppauge NY, USA, 249-294 (arXiv:0903.0978)

# Ray-tracing in Kerr metric

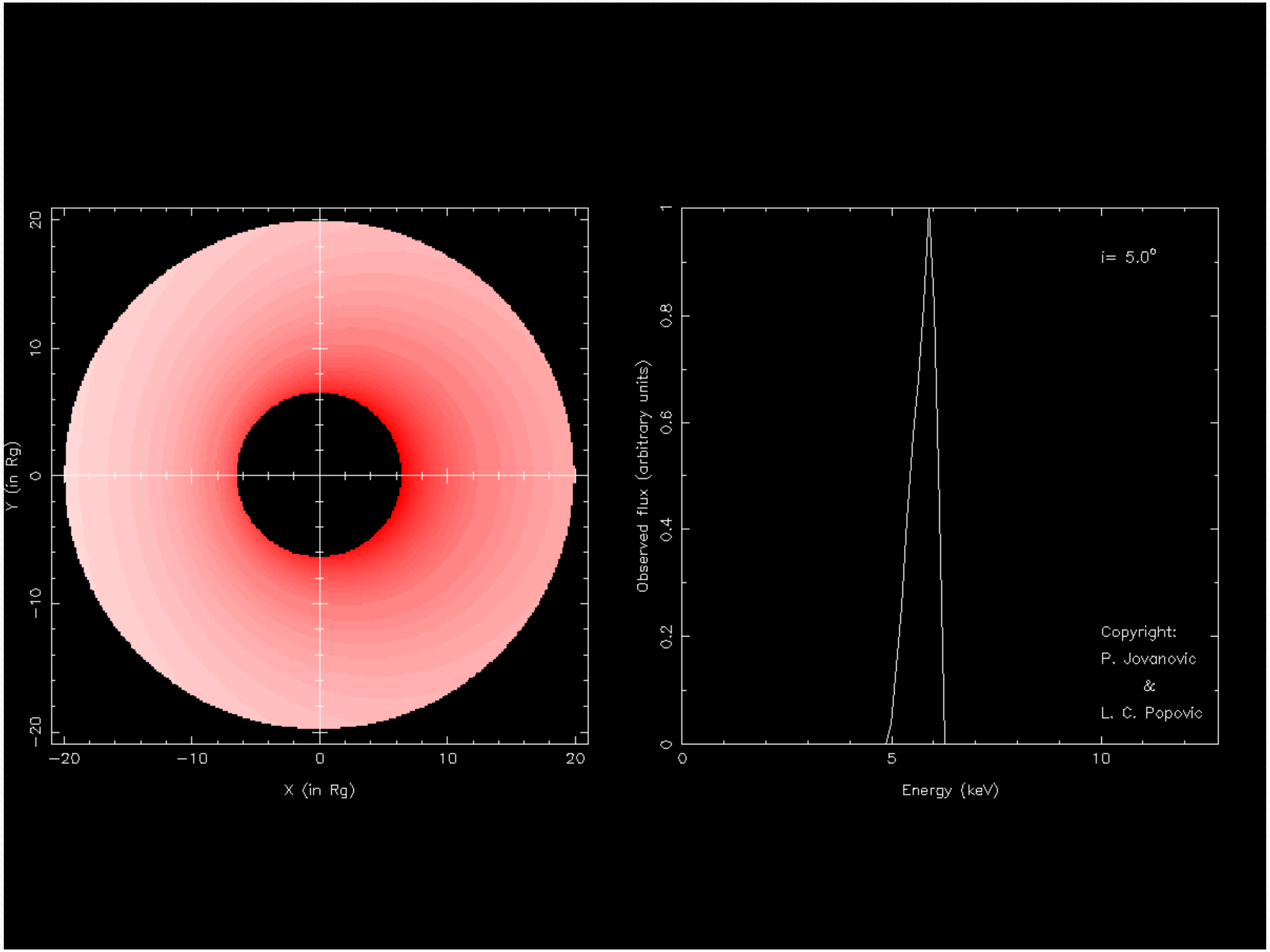



- Surface emissivity of the disk: $\varepsilon(r) = \varepsilon_0 \cdot r^q$
- Total observed flux: $F_{obs}(E_{obs}) = \int_{image} \varepsilon(r) \cdot g^4 \delta(E_{obs} - gE_0) d\Xi, \quad g = \frac{\nu_{obs}}{\nu_{em}}$

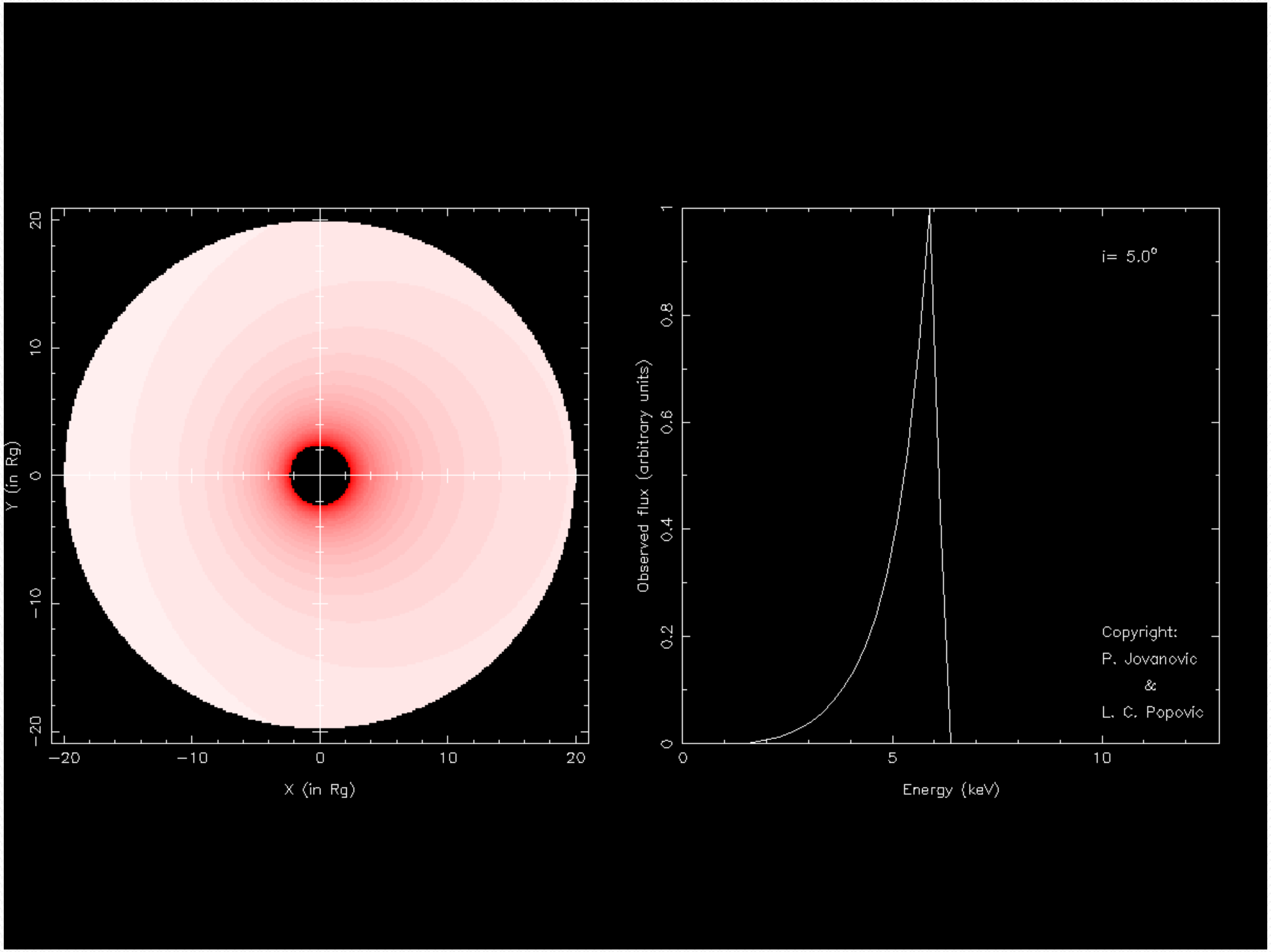
# Numerical simulations of a highly inclined accretion disk ($i$=75°) for different values of angular momentum parameter $a$ (left) and the corresponding profiles of the Fe Kα line (right)

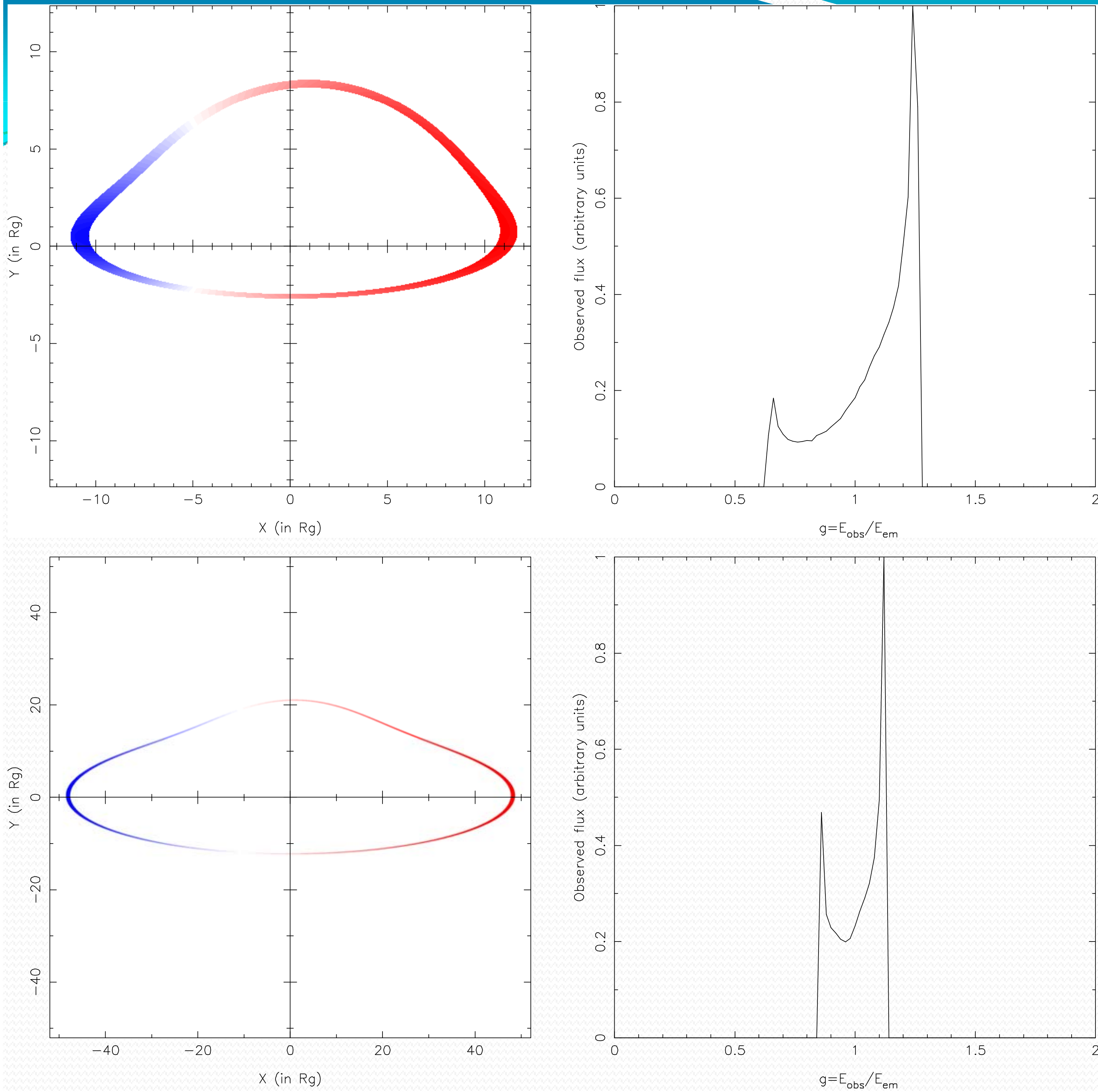


## Numerical simulations of an accretion disk in Schwarzschild metric for different inclination angles *i* (left) and the corresponding profiles of the Fe Kα line (right)



# 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)



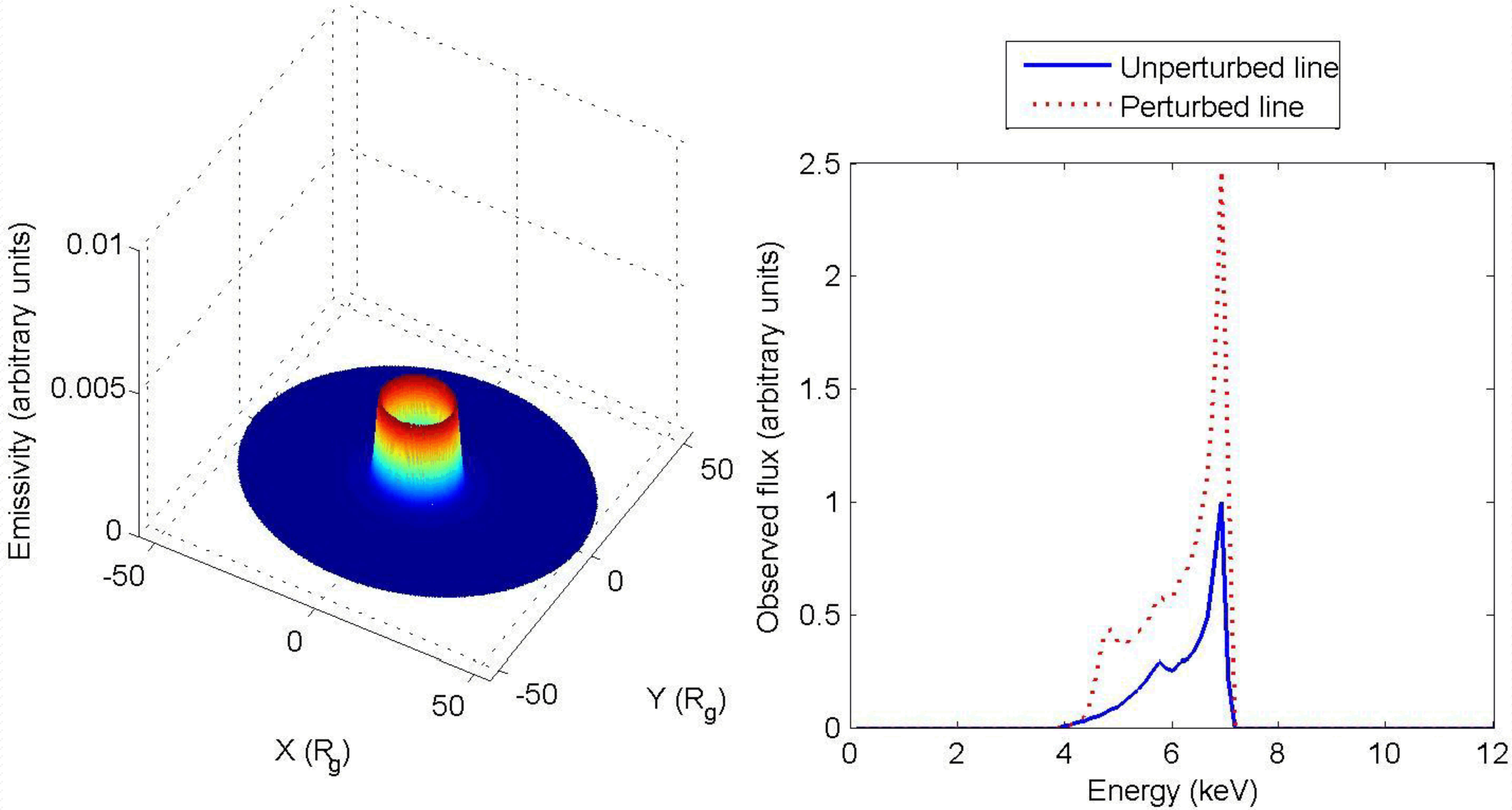



*Left:* illustrations of the Fe Kα line emitting region in form of narrow annulus , extending from:
$R_{in}$ = 10 $R_g$ to $R_{out}$ = 11 $R_g$ (top) and $R_{in}$ = 50 $R_g$ to $R_{out}$ = 51 $R_g$ (bottom).

*Right:* the corresponding Fe Kα line profiles.

P. Jovanović & L. Č. Popović, 2008, *Fortschr. Phys*. **56**, No. 4 – 5, 456

# Modeled variations of the Fe Kα line due to disk emissivity perturbations



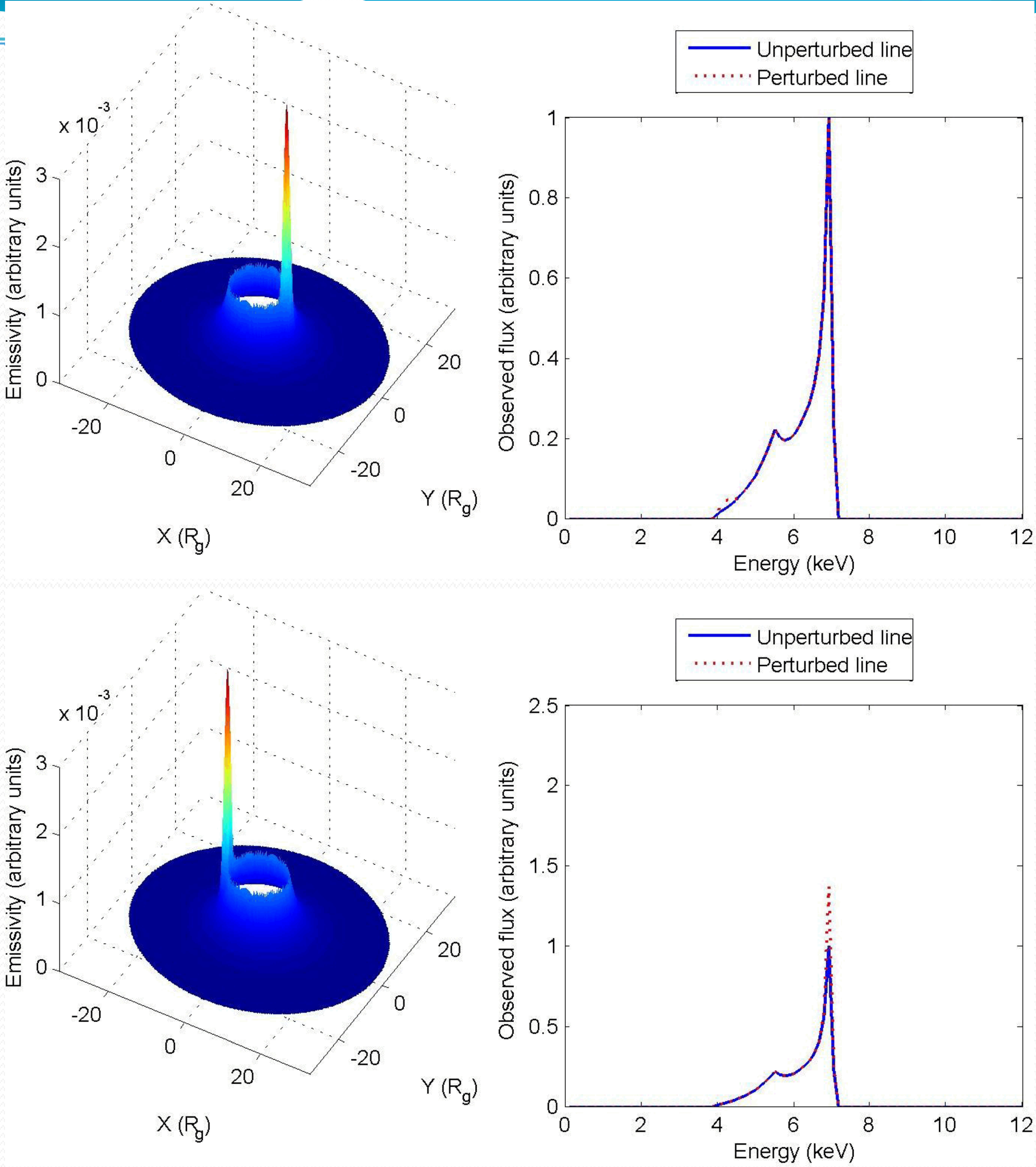

Numerical simulations of disk emissivity perturbations in Schwarzschild metric and the corresponding variations of the Fe Kα line profile

$$\varepsilon_1(r) = \varepsilon(r) \cdot \left( 1 + \varepsilon_p \cdot e^{-\left(\frac{r - r_p}{w_p}\right)^2} \right)$$

Numerical simulations of emissivity perturbations along the receding (top) and approaching (bottom) side of the disk in Schwarzschild metric and the corresponding variations of the Fe Kα line profile

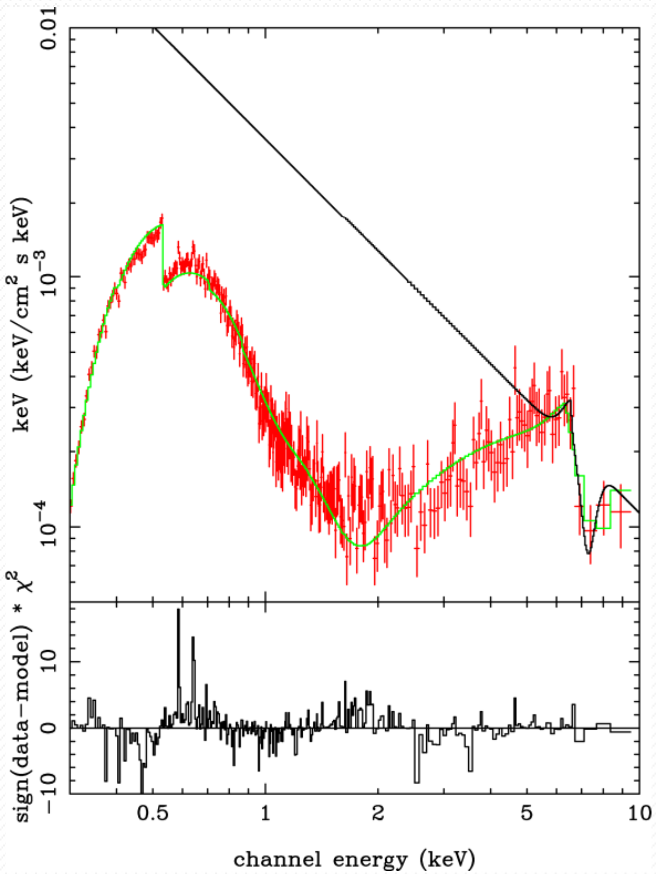
$$\varepsilon_2(x_p,y_p)=\varepsilon(r(x_p,y_p))\cdot\left(1+\varepsilon_p\cdot e^{-\left(\left(\frac{x-x_p}{w_x}\right)^2+\left(\frac{y-y_p}{w_y}\right)^2\right)}\right)$$

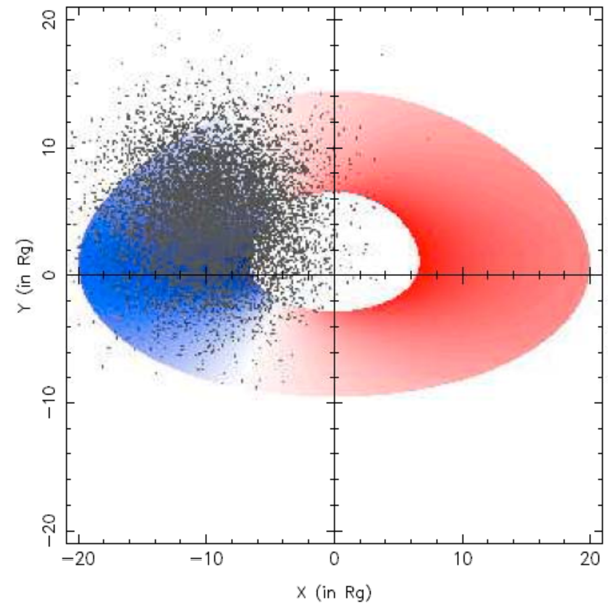
Jovanović, P., Popović, L. Č., Stalevski, M., Shapovalova, A. I. 2010. *ApJ*, 718, 168

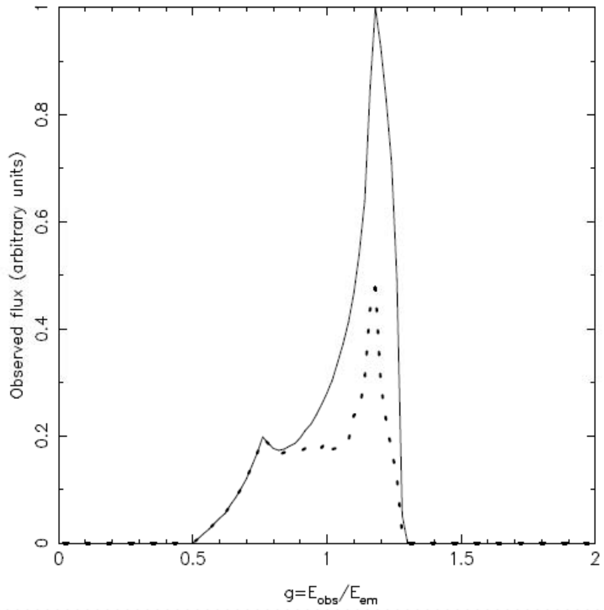


# A model of X-ray absorption region

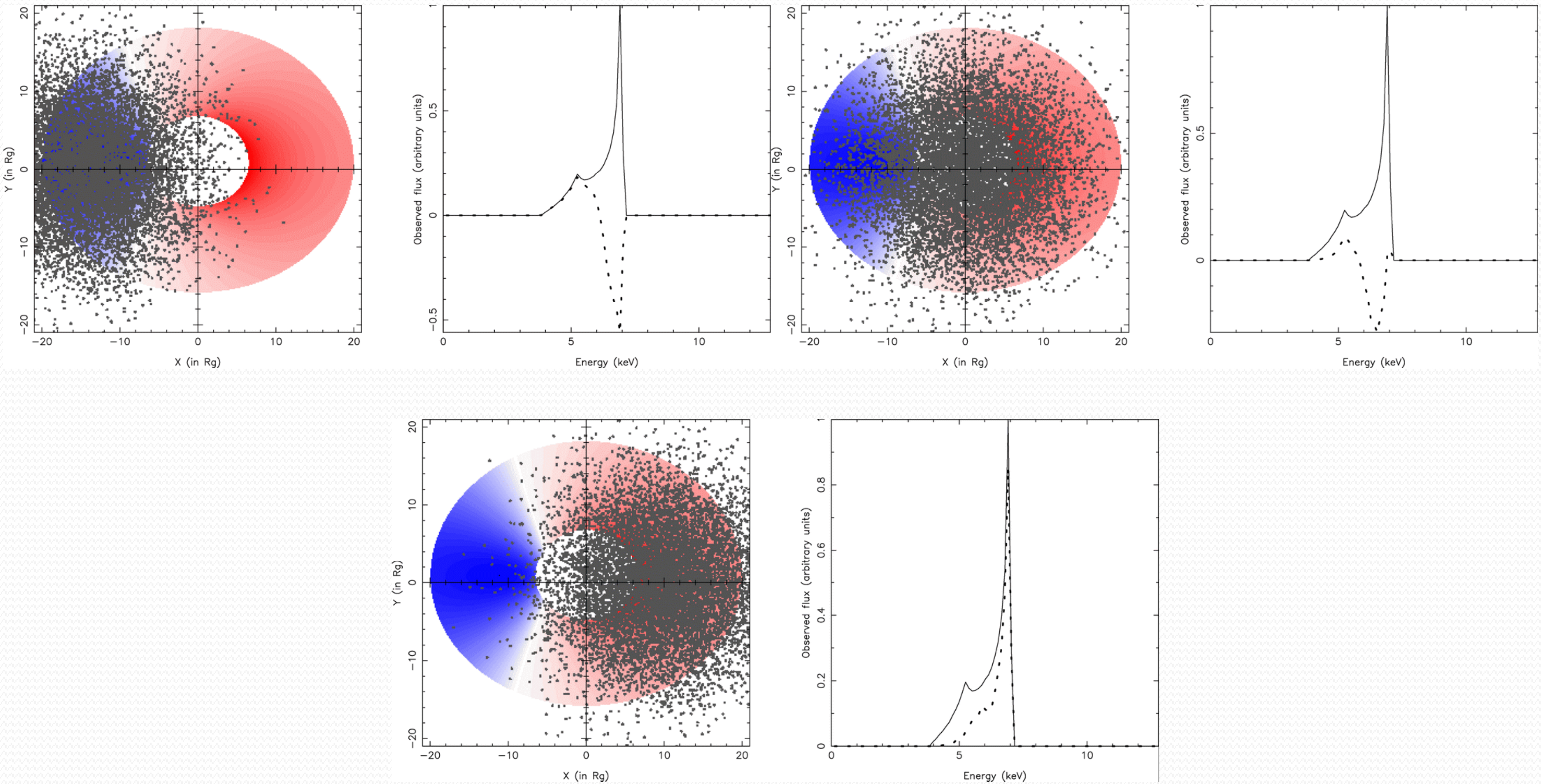
- composed from a large number of small spherical absorbing clouds which have normal distribution



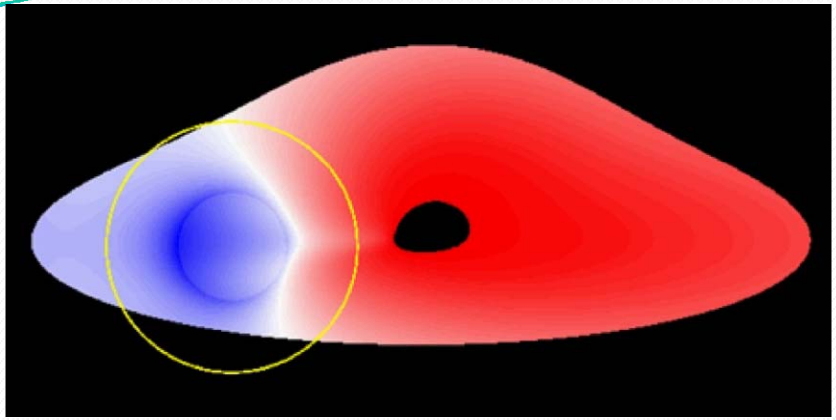

- Done et al. 2007, MNRAS, 374, L15: sharp feature at ~7 keV results from absorption/scattering/emission of iron Kα lines in the wind and can be fitted by P Cygni profile




Jovanović, P., Popović, L. Č., Simić, S. 2009, *NARev*, 53, 156

# Gravitational microlensing

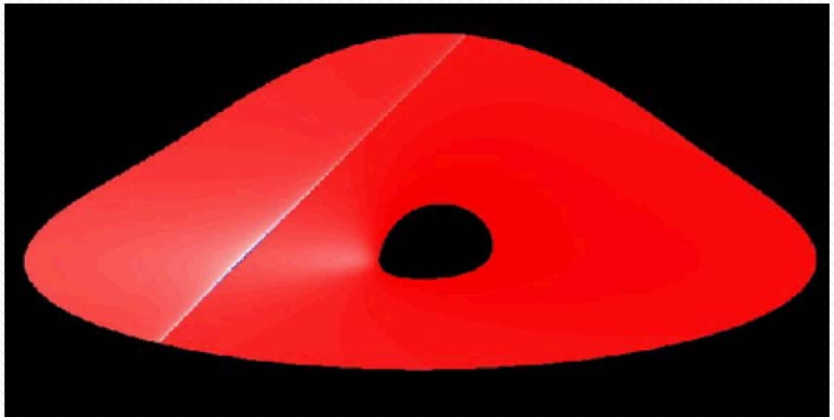
- **Point-like**



$$A(X,Y)=\frac{u^2(X,Y)+2}{u(X,Y)\sqrt{u^2(X,Y)+4}}$$

$$u(X,Y)=\frac{\sqrt{(X-X_0)^2+(Y-Y_0)^2}}{\eta_0}$$

- **Straight-fold caustic**

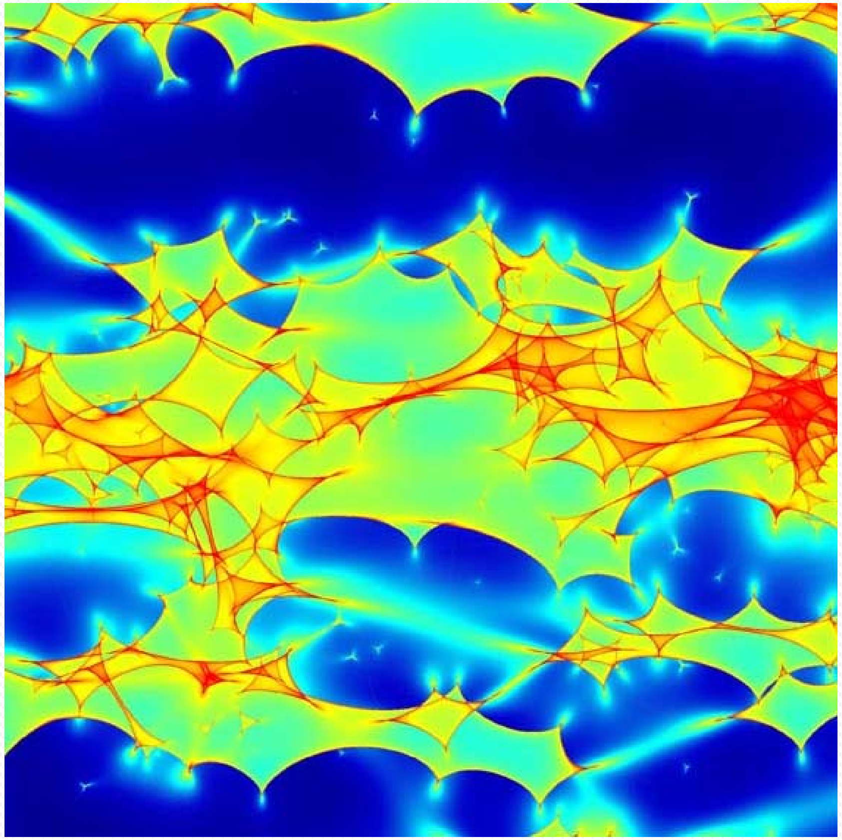


$$A(X,Y)=A_0+\frac{K}{\sqrt{\kappa(\xi-\xi_c)}}\cdot H(\kappa(\xi-\xi_c))$$

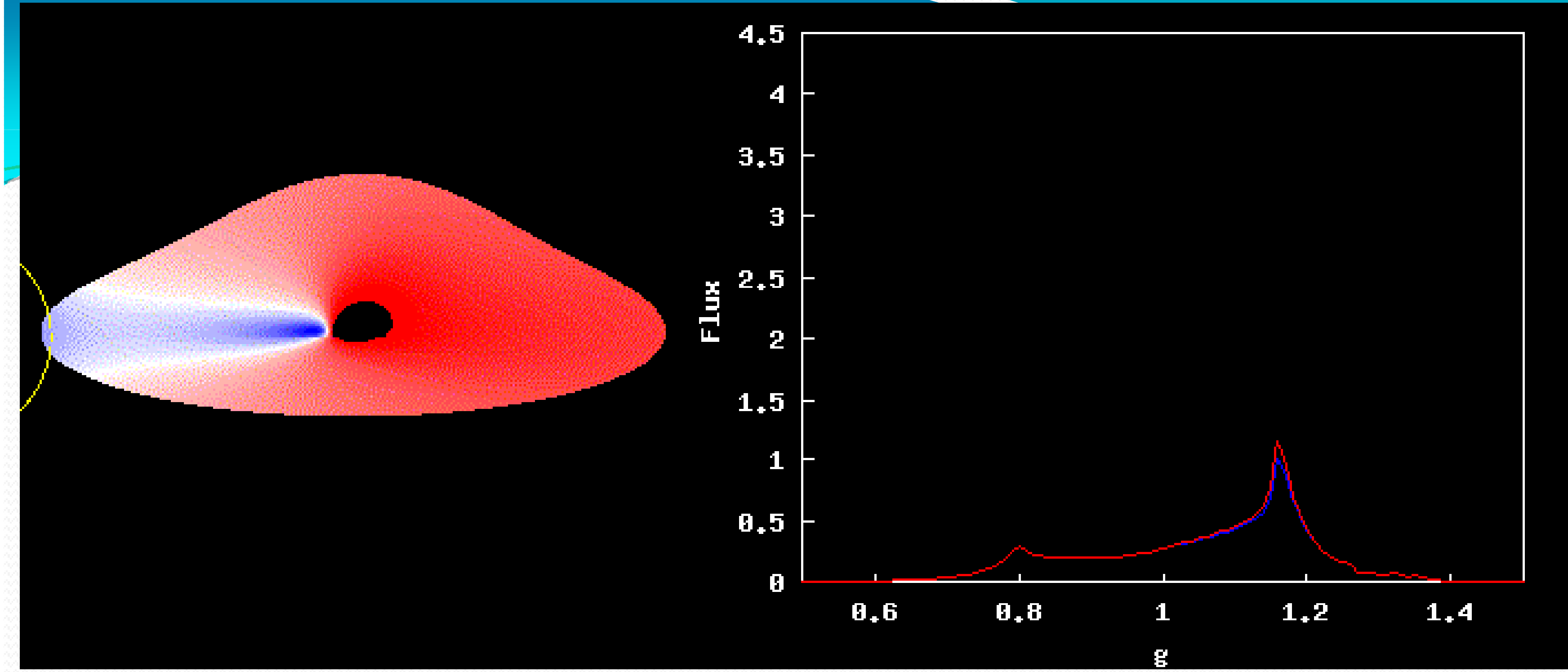
$$K=A_0\beta\sqrt{\eta_0}$$

- **Microlensing magnification map**

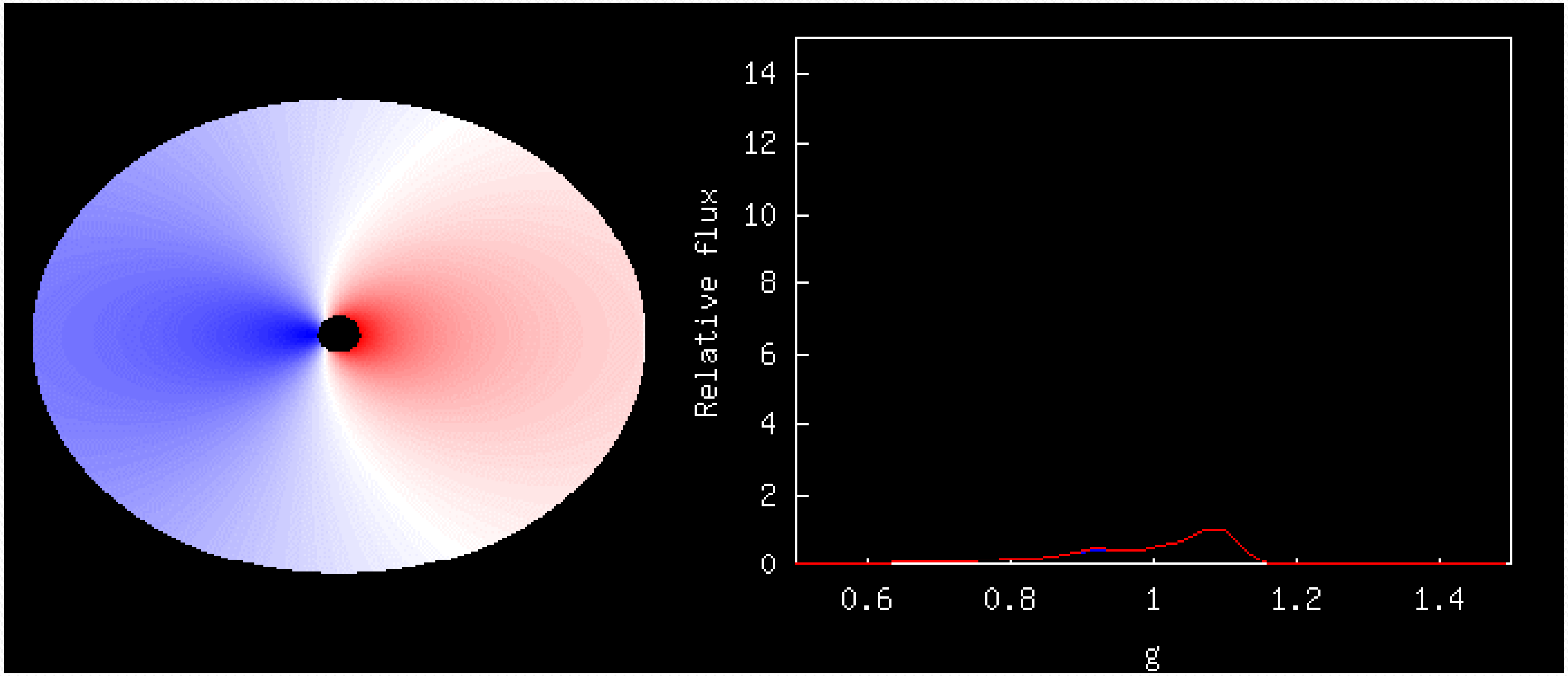
$$\vec{y}(\vec{x})=\vec{x}-\sum_{i=1}^{N} m_i\frac{\vec{x}-\vec{x}_i}{|\vec{x}-\vec{x}_i|^2}-\begin{bmatrix}k_c+\gamma & 0\\ 0 & k_c-\gamma\end{bmatrix}\vec{x}$$



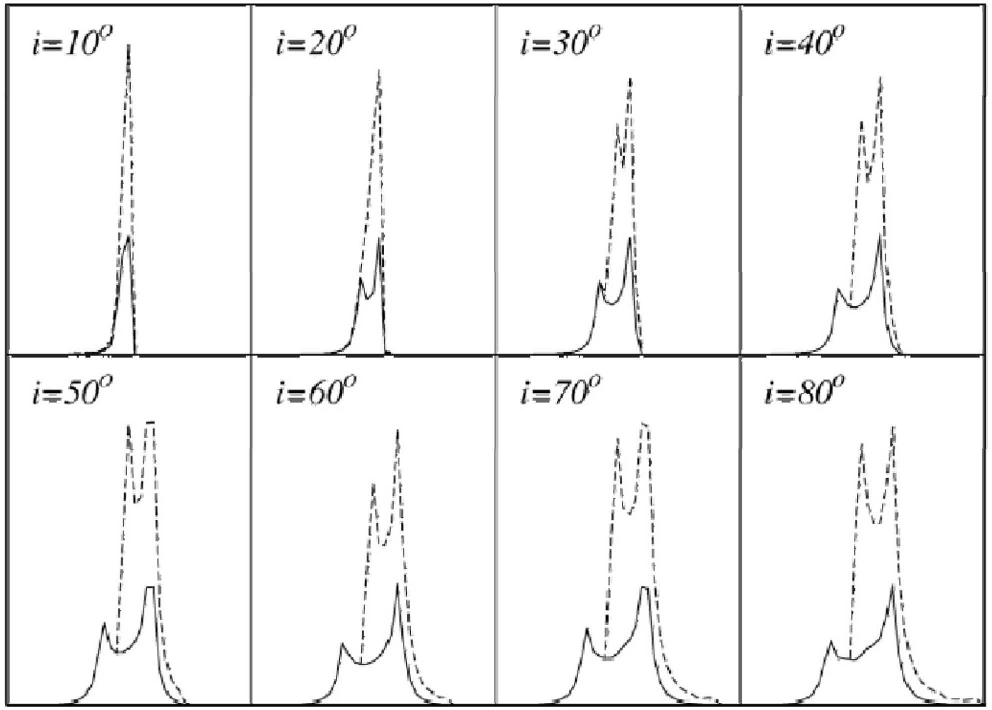
Microlensing magnification map for image A of QSO 2237+0305 ($k_c = 0.36$, $\gamma = 0.4$)



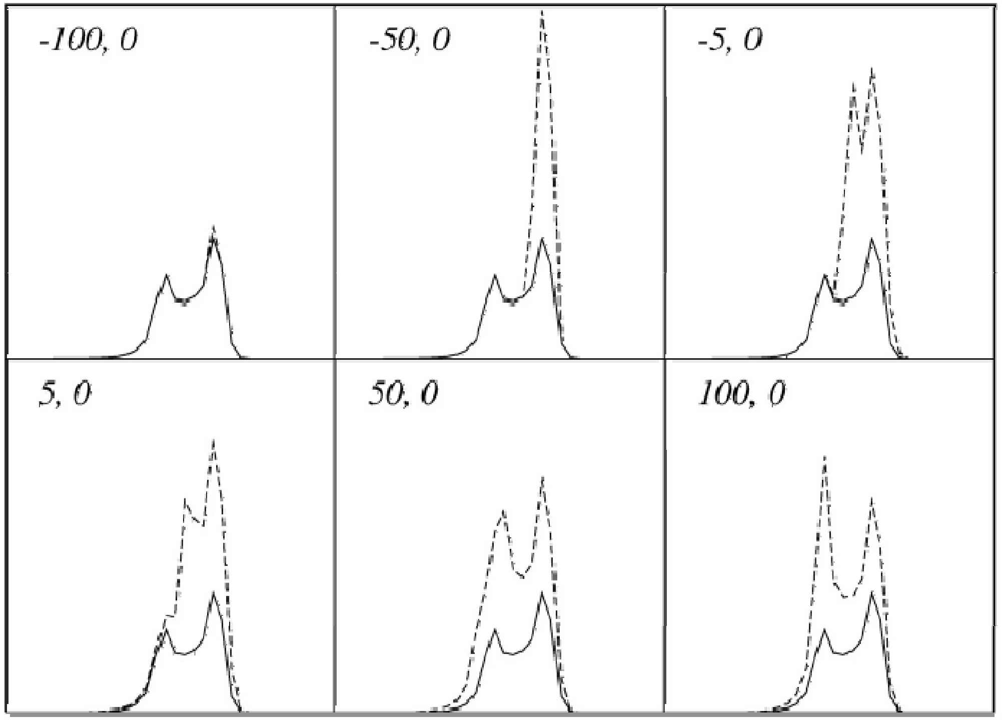

Popović, L. Č., Jovanović, P., Bon, E., Dimitrijević, M. : 2002, Publ. Astron. Obs. Belgrade, 73, 49



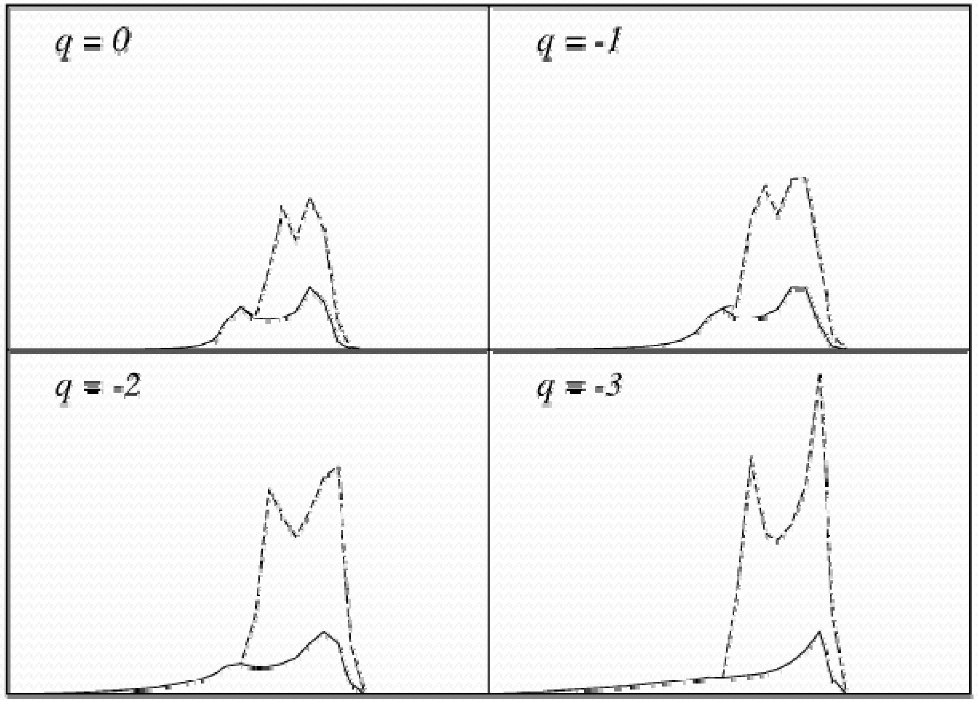

Popović, L. Č., Jovanović, P., Mediavilla, E. G., Muñoz, J. A. 2003. *A&AT*, 22, 719



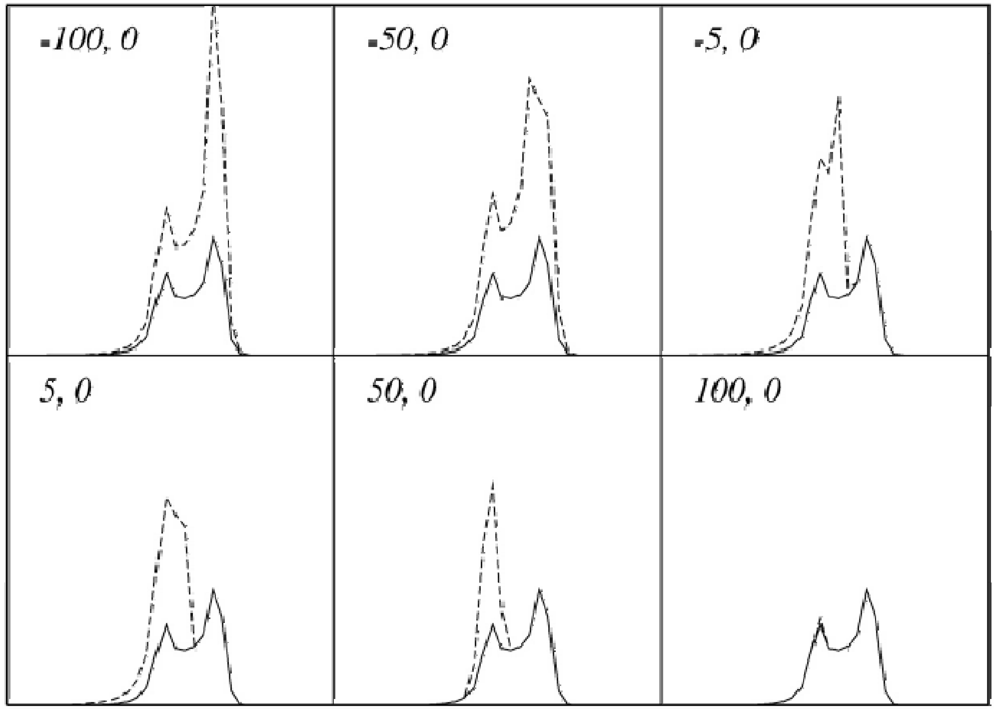
$i=10^o$
$i=20^o$
$i=30^o$
$i=40^o$
$i=50^o$
$i=60^o$
$i=70^o$
$i=80^o$

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

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

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

# Conclusions

1. We investigated the Fe Kα line emitted from the innermost parts of accretion disk around SMBH using numerical simulations based on ray-tracing method in Kerr metric

2. The Fe Kα line is useful tool for:

- studying space-time geometry in vicinity of SMBH
- determination of black hole properties
- probing strong gravity effects and test GR predictions
- studying accretion physics around SMBH

# References


1. Jovanović, P., Popović, L. Č., Stalevski, M., Shapovalova, A. I. 2010. *ApJ*, 718, 168
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10. Popović, L. Č., Jovanović, P., Bon, E., Dimitrijević, M. S. 2002. *Publ. Astron. Obs. Belgrade*, 73, 49

# Thank you for attention!