Modeling of Changes in Shape of the Iron Line During the Microlensing Event

Lukáš Ledvina & David Heyrovský

Institute of Theoretical Physics – Charles University in Prague
http://www.mff.cuni.cz

29$^{\text{th}}$ August 2014

Outline

Gravitational lensing – example

Einstein cross (QSO 2237+0305)

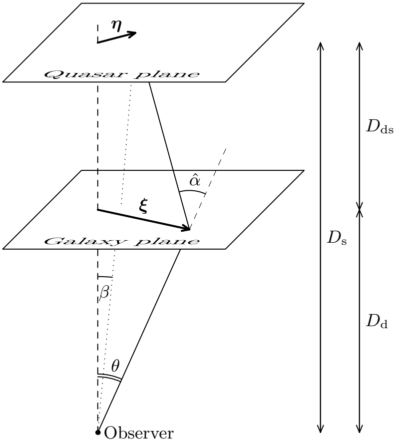
Gravitational lensing I.

- First post-Newtonian approximation of GR
- Deflection angle: one-point lens

$$\hat{\boldsymbol{\alpha}} = \frac{4GM}{c^2} \frac{\boldsymbol{\theta}}{\theta^2}$$

- Continuous matter (thin lens)

$$\hat{\boldsymbol{\alpha}}(\boldsymbol{\theta}) = \frac{4G}{c^2 D_\mathrm{d}} \int \mathrm{d}^2\theta' \varrho(\boldsymbol{\theta}') \frac{\boldsymbol{\theta} - \boldsymbol{\theta}'}{|\boldsymbol{\theta} - \boldsymbol{\theta}'|^2}$$



Gravitational lensing II.

- Lens equation $\left(\boldsymbol{\alpha}(\boldsymbol{\theta}) = \frac{D_{\mathrm{ds}}}{D_{\mathrm{s}}}\hat{\boldsymbol{\alpha}}\left(D_{\mathrm{d}}\boldsymbol{\theta}\right)\right)$

$$\boldsymbol{\beta} = \boldsymbol{\theta} - \boldsymbol{\alpha}(\theta)$$

- Critical surface density

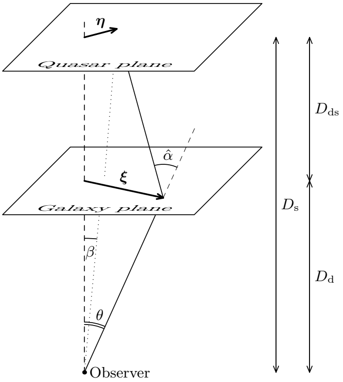
$$\varrho_{\mathrm{cr}} = \frac{c^2}{4\pi G}\frac{D_{\mathrm{s}}}{D_{\mathrm{d}}D_{\mathrm{ds}}}$$

- Convergence κ

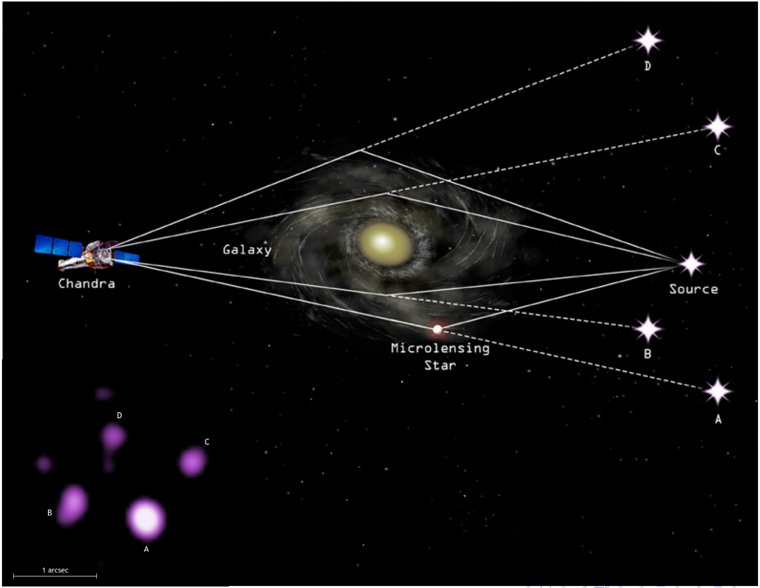
$$\varrho(D_{\mathrm{d}}\boldsymbol{\theta}) = \varrho_{\mathrm{cr}}\kappa(\theta)$$

- Einstein radius

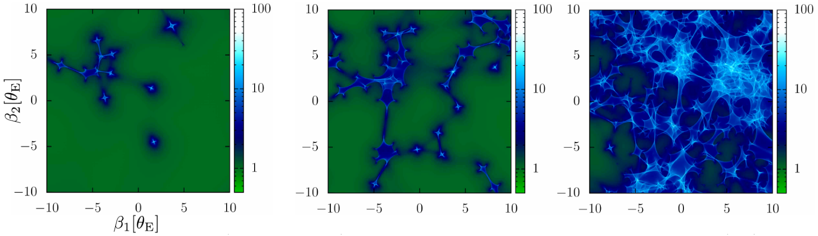
$$\theta_{\mathrm{E}} = \sqrt{\frac{4GM}{c^2}\frac{D_{\mathrm{ds}}}{D_{\mathrm{d}}D_{\mathrm{s}}}}$$



Connection between macro- and micro-lensing



Amplification maps



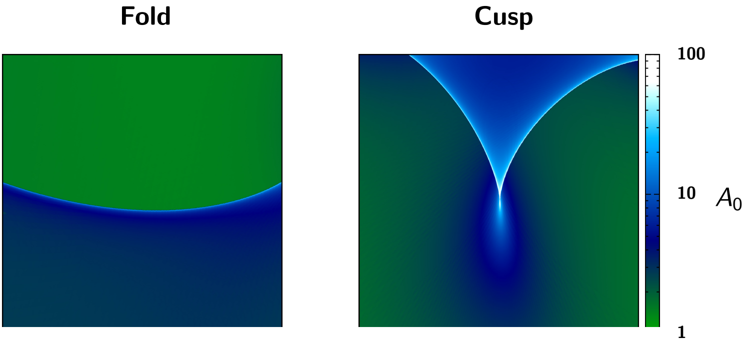
Amplification maps

- In source plane
- Convergence $\kappa_s \in \{0.10, 0.20, 0.55\}$
- Interstellar distances $5.60\,\theta_E$, $3.90\,\theta_E$, $2.39\,\theta_E$

Flux

$$F_{obs}(\alpha_0, \beta_0) = \int_{disk} I_{obs}(\alpha, \beta) A(\alpha - \alpha_0, \beta - \beta_0) \mathrm{d}\alpha \mathrm{d}\beta$$

Amplification maps – detail



Caustic

- Curve where amplification diverges
- Two most common shapes: fold and cusp

Observational data

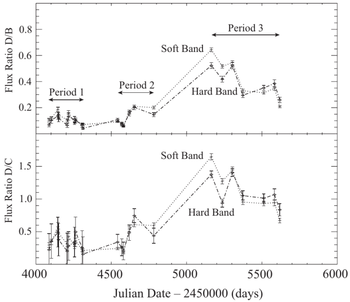


Figure 4. Soft (0.2–2 keV) and hard (2–10 keV) flux ratios D/B and D/C of RX J1131−1231. Significant energy-dependent microlensing is detected in image D.

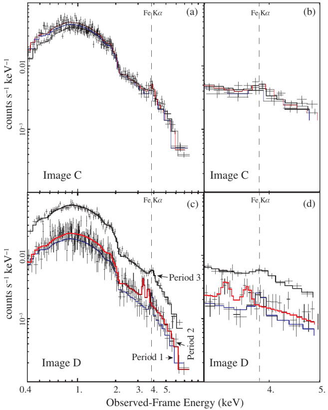


Figure 6. Stacked spectra of images C (panel (a)) and D (panels (c)) for the three periods shown in Figure 4. A closeup of the stacked spectra around the Fe Kα region for images C (panel (b)) and D (panel (d)). The curves are the best-fit absorbed power-law plus Gaussian line models.

(A color version of this figure is available in the online journal.)

RXJ1131–1231

- Microlensing variability in X-rays
- Chartas et al. 2012, ApJ, 757, 137

Caustic model

$$A(\tilde{x},\tilde{y}) = A_0 + \begin{cases} 0 & \text{for} \quad \tilde{y} \geq 0 \\ \sqrt{\frac{-\tilde{y}_0}{\tilde{y}}} & \text{for} \quad \tilde{y} < 0 \end{cases}$$

Straight fold caustic

- $A(\tilde{x},\tilde{y})$ – point source amplification
- A_0 – background amplification
- $\tilde{y}_0$ – caustic strength
- $\tilde{x}$, $\tilde{y}$ – Cartesian coordinates, see later

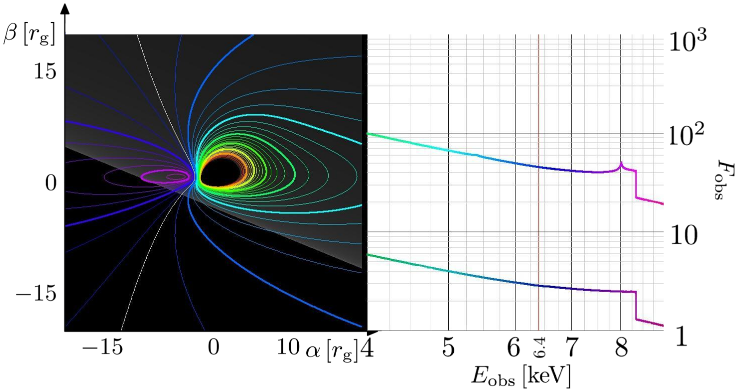
Disk model by Michal Dovčiak

- Kerr BH (spin a) + thin disk
- local emission: photon specific intensity
  continuum: $I^{\mathrm{cont}}_{E,\mathrm{e}} = I^{\mathrm{cont}}_0 E_{\mathrm{e}}^{-\Gamma} r^{-q}$
  iron line: $I^{\mathrm{Fe}}_{E,\mathrm{e}} = I^{\mathrm{Fe}}_0 r^{-q} \delta[E - E_{\mathrm{Fe}}]$
  - $E_{\mathrm{e}} \ldots$ photon energy (emitted)
  - $r \ldots$ Boyer-Lindquist radius
  - $\Gamma \ldots$ spectral index
  - $q \ldots$ radial index
- observed photon energy $E_{\mathrm{obs}} = E_{\mathrm{e}} g$
  g … Doppler + gravitational shift
- transformation $(r, \varphi)_{B-L} \quad \Rightarrow \quad (\alpha, \beta)$ Cartesian coordinates of deflected photons, see Dovčiak et al. (2004)
- observed intensity in given energy band:
  $I^{\mathrm{cont}}_{E,\mathrm{obs}}(\alpha, \beta; q, \Gamma) = I^{\mathrm{cont}}_0 g(\alpha, \beta)^{\Gamma+2} r(\alpha, \beta)^{-q}$
  $I^{\mathrm{Fe}}_{E,\mathrm{obs}} = I^{\mathrm{Fe}}_0 r(\alpha, \beta)^{-q} g(\alpha, \beta)^2 \delta[E - g(\alpha, \beta) E_{\mathrm{Fe}}]$
- disk cutoff at ISCO, at radius including 99% of total flux

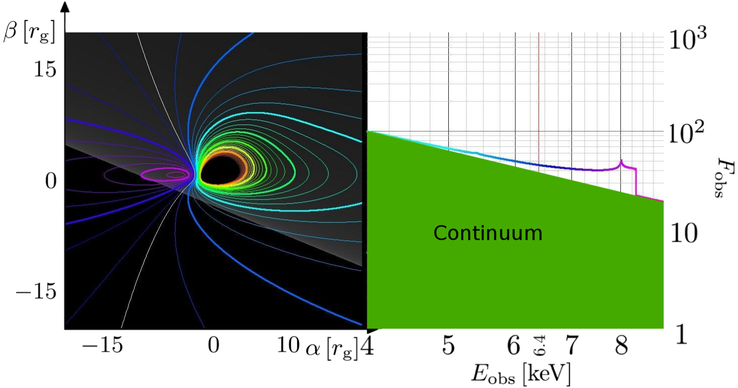
Microlensing event animation

Parameters: $i = 70^\circ$, $a = 1$, $\Gamma = 2$, $q = 3$.

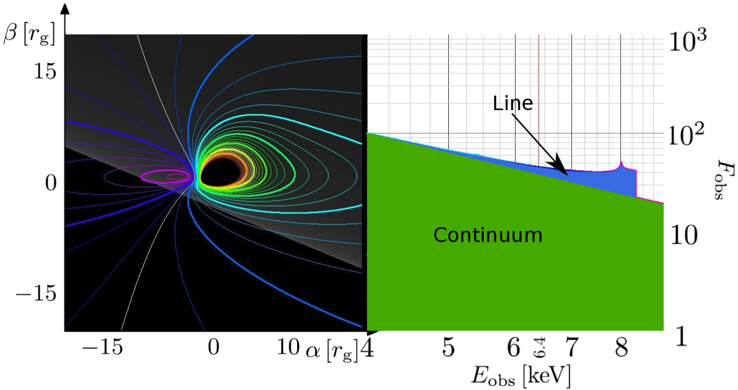
Decomposition of spectrum



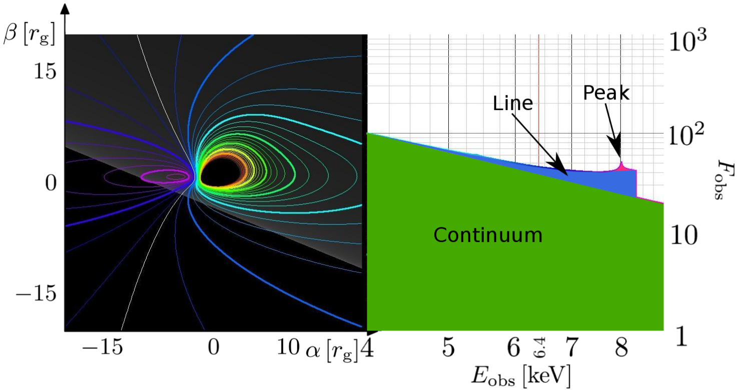
Decomposition of spectrum



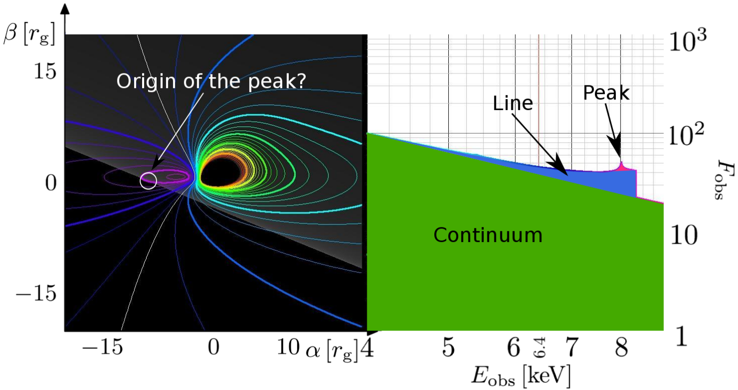
Decomposition of spectrum



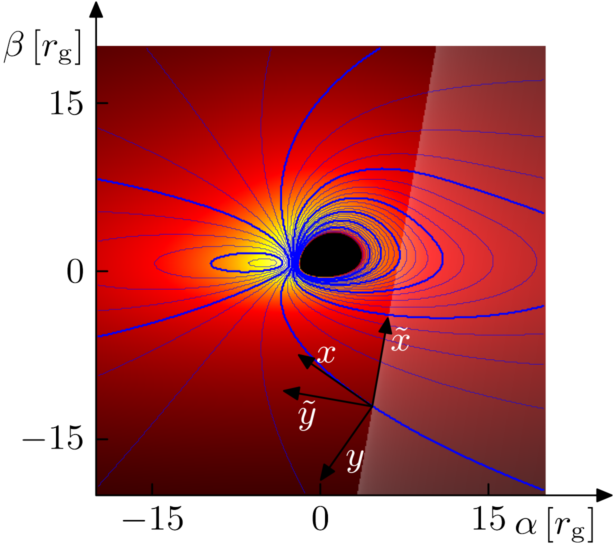
Decomposition of spectrum



Decomposition of spectrum



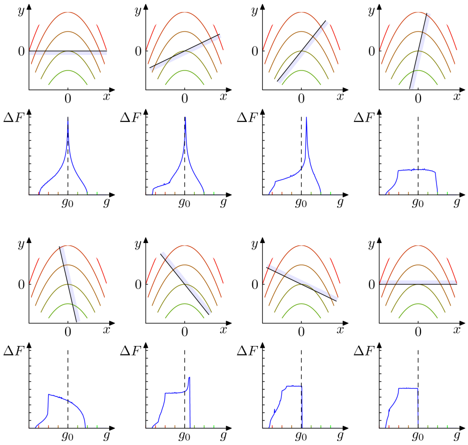
Coordinate systems



Peak modeling

g-factor

- $g(x,y) = g_0 + g_y y + \frac{1}{2} g_{xx} x^2$
- Simplest curved contour

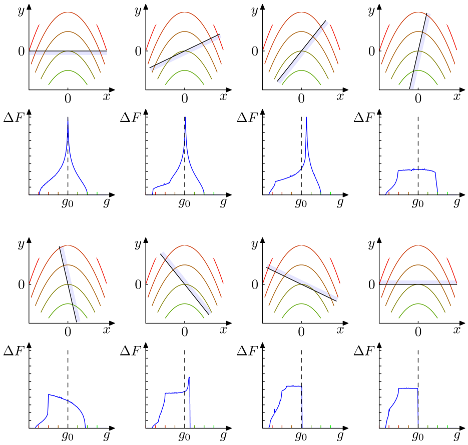


Peak modeling

g-factor

- $g(x,y) = g_0 + g_y y + \frac{1}{2} g_{xx} x^2$
- Simplest curved contour

- Internally tangent $\Rightarrow$ peak

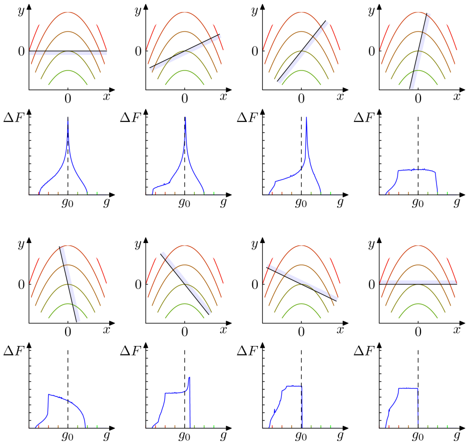


Peak modeling

g-factor

- $g(x,y) = g_0 + g_y y + \frac{1}{2} g_{xx} x^2$
- Simplest curved contour

- Internally tangent $\Rightarrow$ peak
- Externally tangent $\Rightarrow$ edge

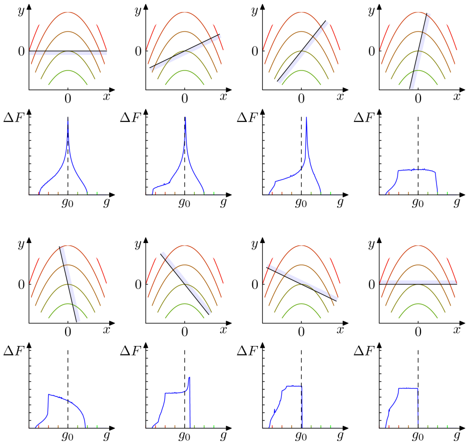


Peak modeling

g-factor

- $g(x, y) = g_0 + g_y y + \frac{1}{2} g_{xx} x^2$
- Simplest curved contour

- Internally tangent $\Rightarrow$ peak
- Externally tangent $\Rightarrow$ edge
- Other orientation $\Rightarrow$ nothing special



Peak modeling

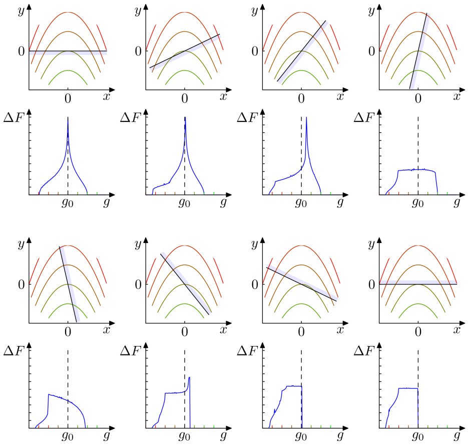
g-factor

- $g(x,y) = g_0 + g_y y + \frac{1}{2} g_{xx} x^2$
- Simplest curved contour

- Internally tangent $\Rightarrow$ peak
- Externally tangent $\Rightarrow$ edge
- Other orientation $\Rightarrow$ nothing special

Main result

For generating spectral feature (i.e. peak or edge) caustic must be tangent to the contours.



Analytical expression (leading terms)

Internally tangent contour to the caustic

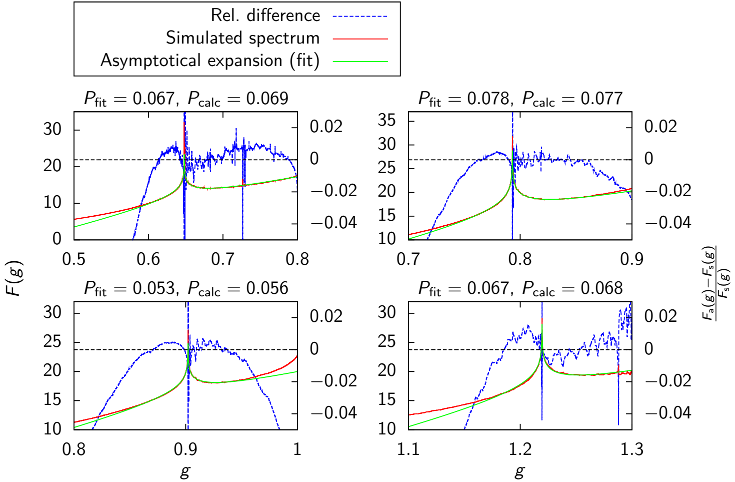
$$\Delta F(E) \approx -I_0 \sqrt{\frac{2}{g_{xx} g_y}} \log |E - g_0 E_{\mathrm{Fe}}|$$

Externally tangent contour to the caustic

$$\Delta F(E) \approx I_0 \sqrt{\frac{2\pi^2}{g_{xx} g_y}} H(E - g_0 E_{\mathrm{Fe}})$$

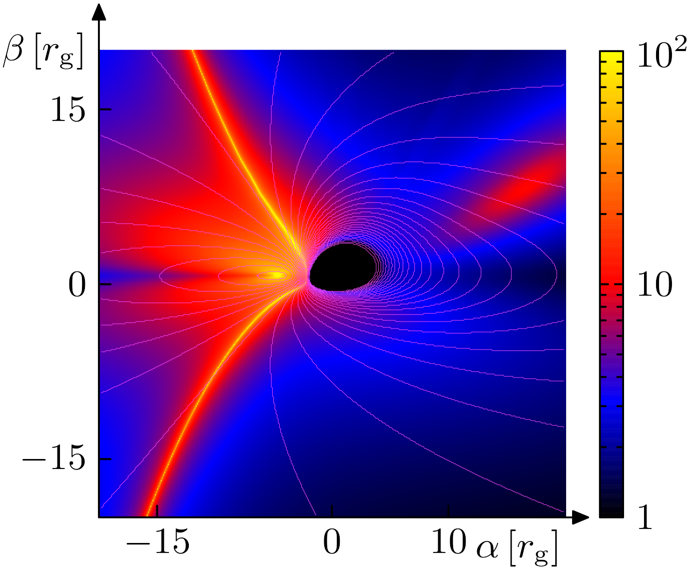
- I_0 – specific intensity at the tangent point
- g_0 – g-factor at the tangent point
- g_y – derivative of the g-factor perpendicular to the caustic
- g_{xx} – second derivative of the g-factor parallel to the caustic

Simulation vs. analytical expression



Qualitative and quantitative agreement!

Peak strength at disk for 70° inclination



Summary

- Microlensing is new method for studying central part of accretion disk.
- Spectral changes in iron line during microlensing event were observed.
- Used models of accretion disk and caustic were shown.
- We introduced here a mechanism of peak and edge generation on lensed iron spectral line.

This work was done in collaboration with Michal Dovčiak, Vjačeslav Sochora and Vladimír Karas of Astronomical Institute of the Academy of Sciences. This research was supported by the Charles University Grant Agency grant GAUK 2000314, the Czech Science Foundation grant GAČR P209/10/1318 and the Specific Academic Research Project SVV-260089.

Thank you for your attention.