

Test of relativistic gravity using the microlensing of broad iron line in quasars

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GR – the most popular theory of gravity

Numerous test verifying the General relativity in the weak-field limit

$$U = \frac{G_N M}{R} \simeq 10^{-6} \left[\frac{M}{M_\odot} \right] \left[\frac{R}{R_\odot} \right]^{-1} \ll 1$$

Many of weak-field limit tests can be done locally, in the Solar System

The “classical” weak-field limit tests of GR:

- Mercury perihelion precession (Le Verrier 1859, Einstein 1916)
- deflection of light by the Sun (Dyson+ 1920, van Biesbroeck '53, Brune Jr.+ '76)
- gravitational redshift (Pound & Rebka '59)

These and many other tests confirm GR and constrain the alternative models of gravity.

GR tests in the strong field regime

Strong-field limit requires observations of exotic objects...

- Attempts of direct imaging of black hole surfaces (Lo+ '98, Krichbaum+ '98, Doeleman+ '12)
- Thermal emission of the black hole accretion disks (Zhang+ '97, Gierlinski+ '01, McClintock+ '06, Shafee+ '06)
- Atomic lines from the surfaces of neutron stars (Lewin+ '93, Cottam+ '02)
- [Relativistically broadened iron line in black hole accretion discs](#) (Fabian+ '00, Tanaka+ '95, Reynolds & Nowak '03)
- QPOs in neutron star and black hole systems (Strohmayer '01, Zhang+ '98)

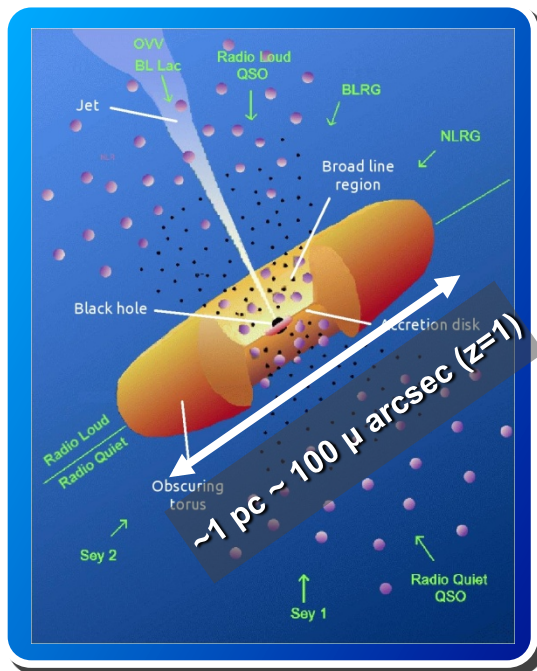
No deviation from GR is observed till now,
[though many of the above test significantly depend on the details of the astrophysical nature of the sources, not the GR itself.](#)

Resolving the black hole surroundings?

„A picture is worth a thousand spectra“ (Psaltis '08)

Perhaps, the most straight forward way to test the gravity theories in the strong-field regime is via the measurement of laws of celestial mechanics in the black surroundings.

Requires accurate spatial (imaging) and velocity (spectra) information.



Urry & Padovani (1995)

The apparent size of the central region of an AGN is $\sim 100 \mu \text{ arcsec}$ at $z=1$.

Accretion disk (10^{-2} pc) is $\sim 1 \mu \text{ arcsec}$
SMBH (10^{-4} pc) is $\sim 0.01 \mu \text{ arcsec}$.

➔ The required spatial information is accessible only in the radio band and only for the closest sources
But the lines are only in X-rays.

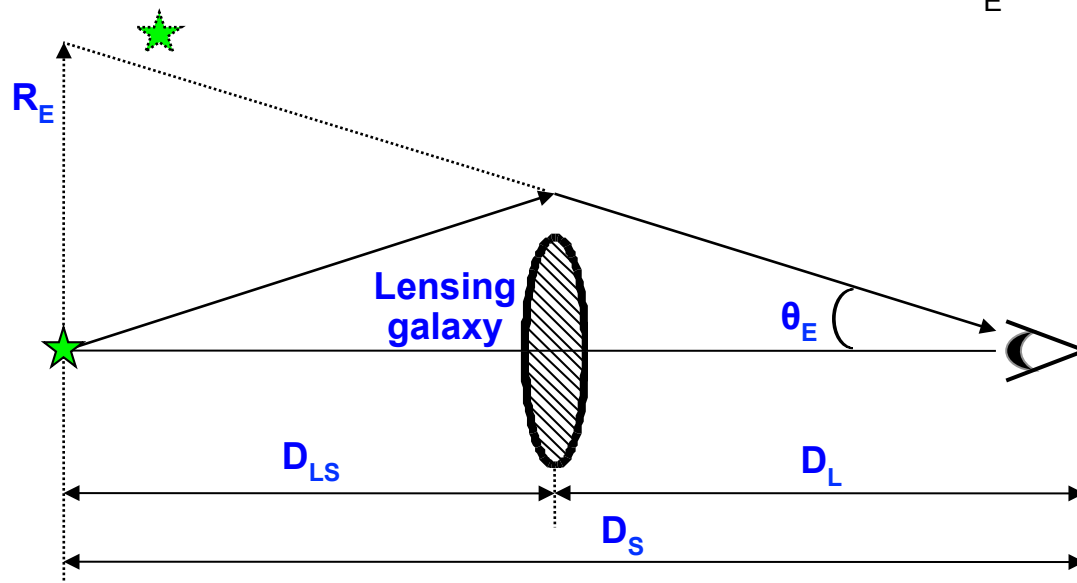
Gravitational lensing

To obtain the required spatial information in X-rays we can use the „lenses“ created by the Nature.

This is possible via the effect of the **gravitational (micro)lensing**.

Gravitational lensing leads to creation of several distorted and magnified images of the source.

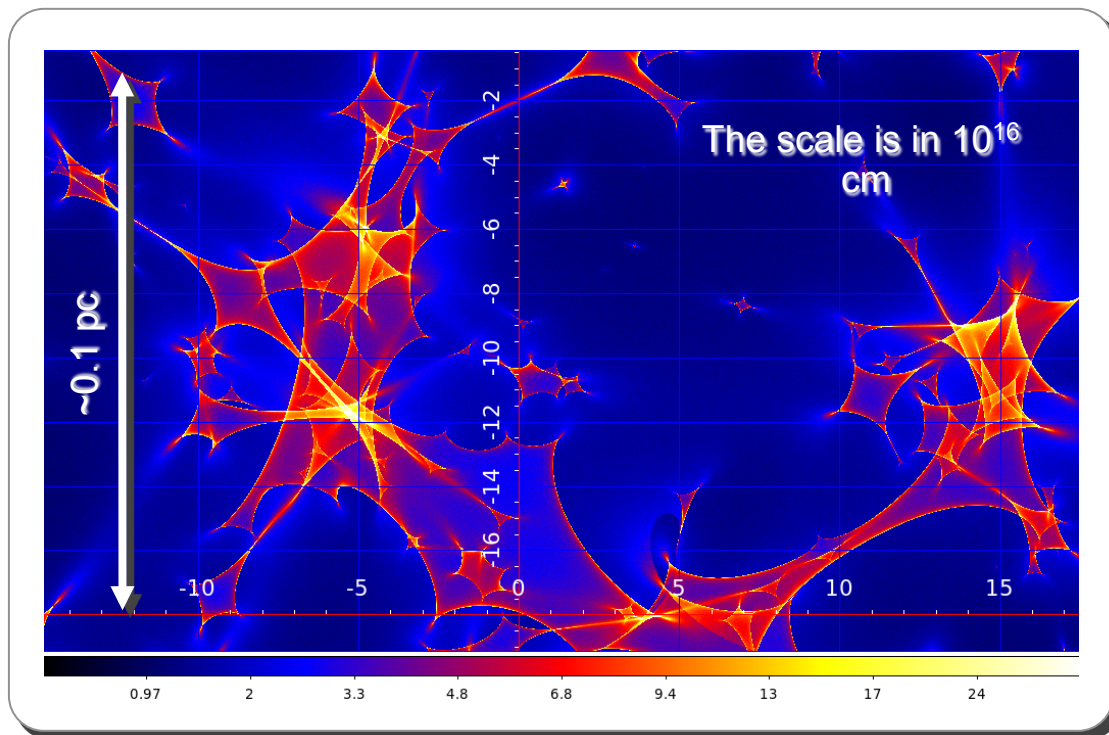
The characteristic spatial scale of the lensing is set by the Einstein radius R_E .



$$\theta_E = [4GM/c^2 * D_{LS}/(D_S D_L)]^{0.5}$$
$$R_E \sim 4 \times 10^{16} (M/M_{\text{Sun}})^{0.5} \text{ cm}$$

Gravitational microlensing

Many stars-microlenses → complicated magnification pattern



The lens and the source are moving with respect to each other at $v \sim 1000$ km/s, leading to a constant change in magnification.

Magnification **amplitude** and **duration** depends on the source size:

$$\mu_{\text{micro}} \sim (R_E/R)^{0.5} \text{ and } \Delta t = R/v$$

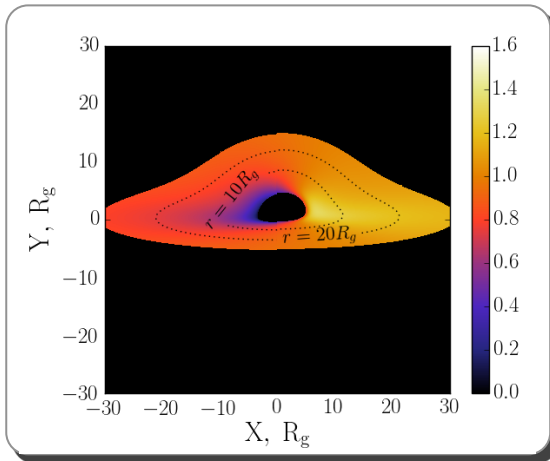
The lines of high magnification – the caustics – are able to literally „scan“ the source as they move over it.



Their motion can give the required spatial information.

Line emission of the black hole accretion disk

To estimate the potential of microlensing, we first attempted to create a simplified model of the line emission of an accretion disk around a black hole.



The redshift „map“ of the accretion disk, computed for inclination $i=80^\circ$

A „ray shooting“ technique to compute the line shape:

- Photons start from a „screen“ perpendicular to the line of sight.
- Photons are back-traced till they reach the equatorial plane (accretion disk) or event horizon.
- Photons crossing the plane N times form an N-order image.
- Photons crossing the plane inside ISCO do not contribute to the observed flux.

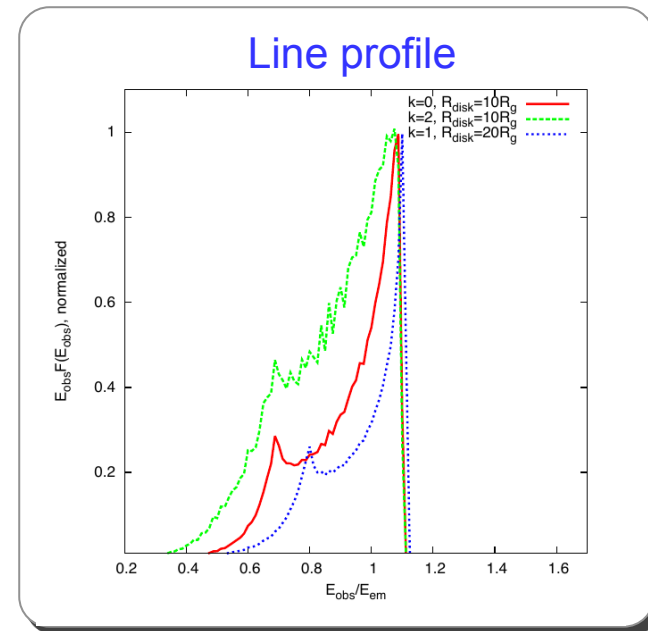
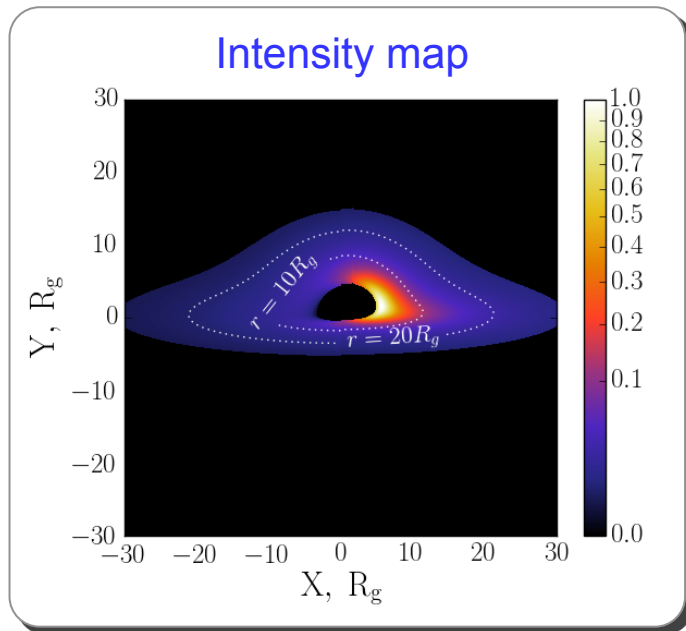
The corresponding redshift in Boyer-Lindquist coordinates can be expressed as:

$$E_{obs} = \delta_{em} E_{em} \left[\sqrt{\frac{\Sigma \Delta}{A}} - \frac{2R_g a r \sin \theta}{\sqrt{\Sigma A}} \cos \alpha_{em} \right]$$

Line emission of the black hole accretion disk

The line profile can be computed convolving the maps of blue/red shifts $\delta_{\text{obs}} = E_{\text{obs}}/E_{\text{em}}$ with the disk intensity profile $I_{\text{em}}(r) \sim r^{-k}$:

$$F(E_{\text{obs}}) = \int \int_{\alpha, \beta} \delta_{\text{obs}}^3(\alpha, \beta) I_{\text{em}}(r(\alpha, \beta)) d\alpha d\beta$$

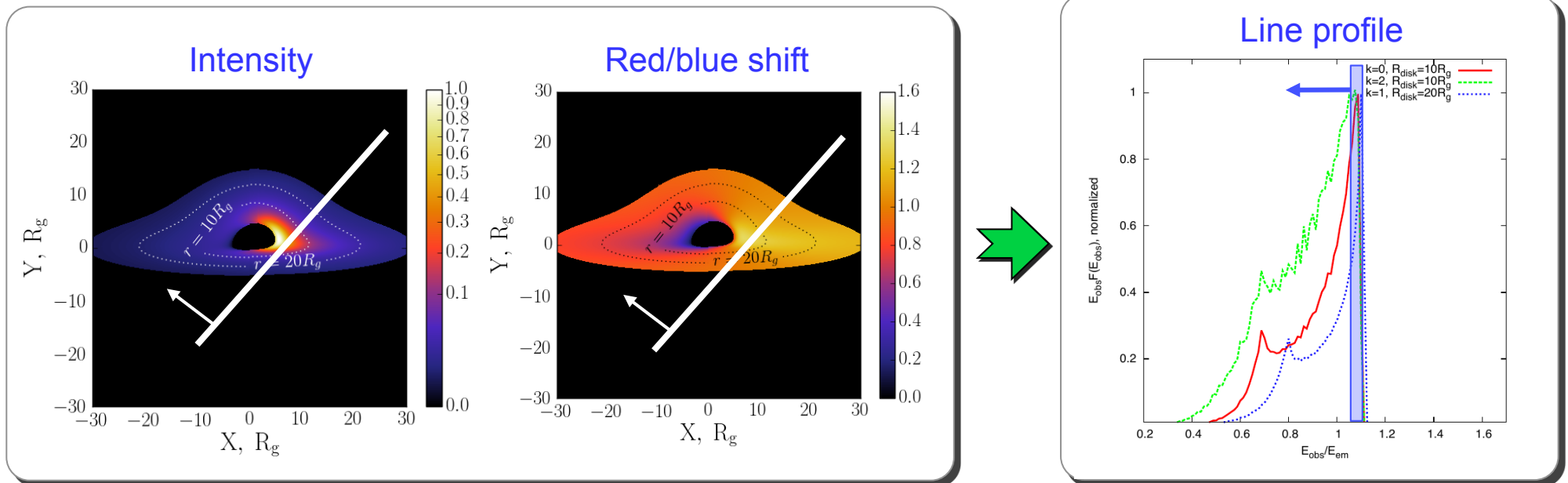


Qualitative picture of the microlensing influence

As the microlensing caustic moves along the accretion disk, it „scans“ it both in terms of intensity and redshift.

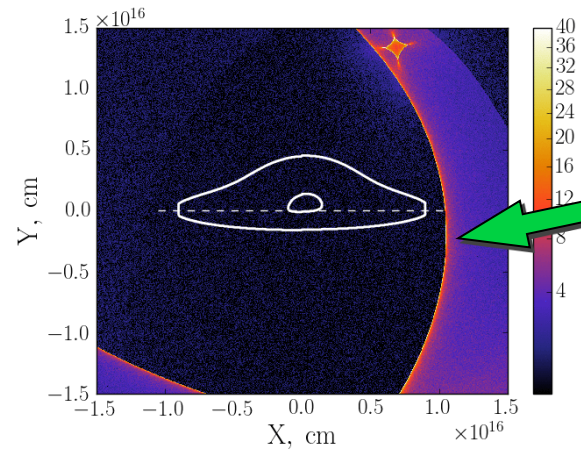
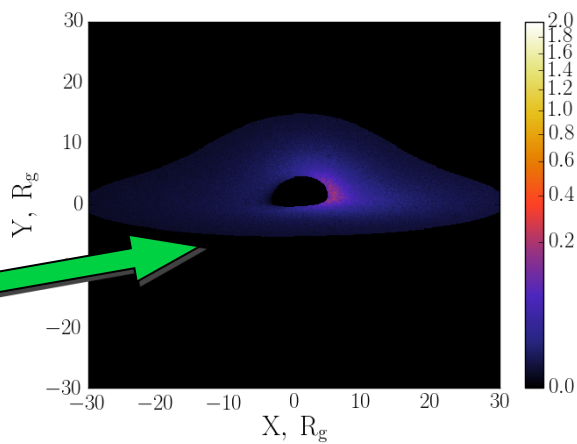
This results in the selective magnification of the blue or red edges of the line profile.

The caustic scans the disk with the constant cadence, enabling the distance measurement as $r \sim t$.

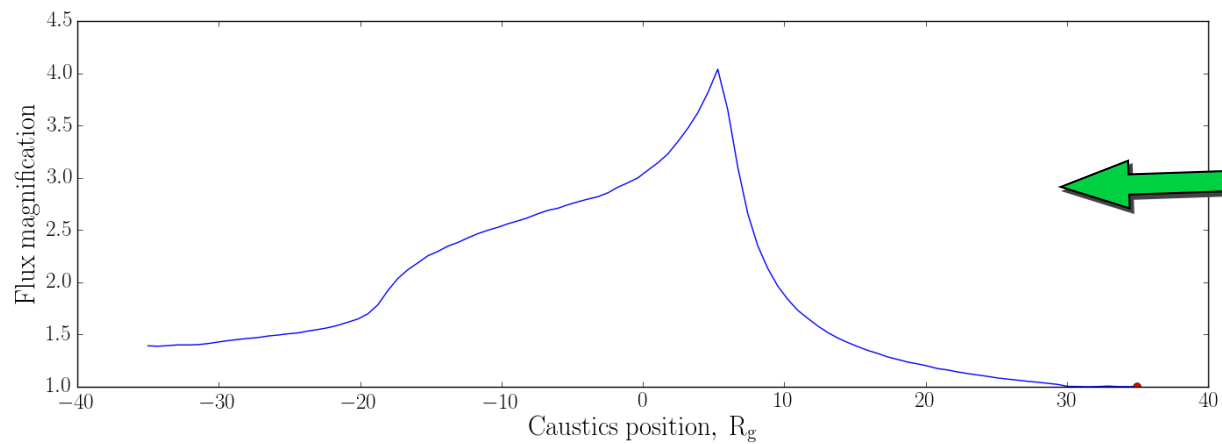


Qualitative picture of the microlensing influence

Magnified
disk
intensity



Microlensing
caustic

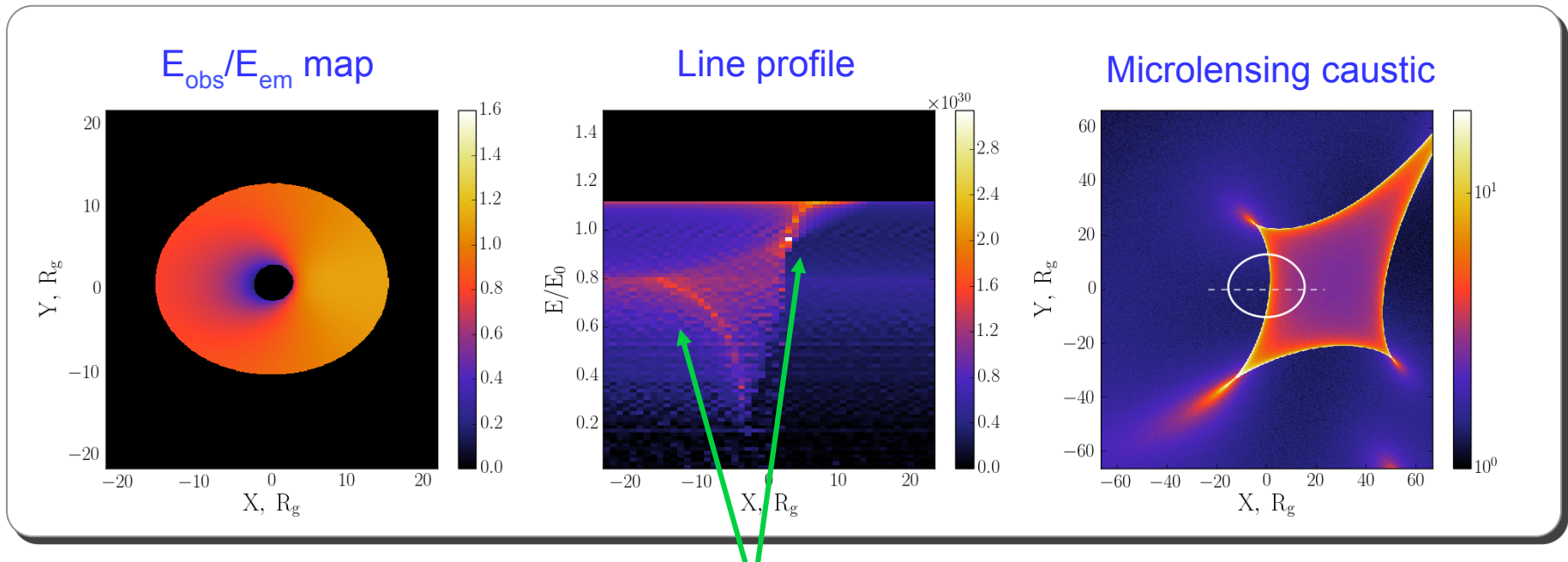


Total flux
variability

Microlensing „portrait“ of an emission line

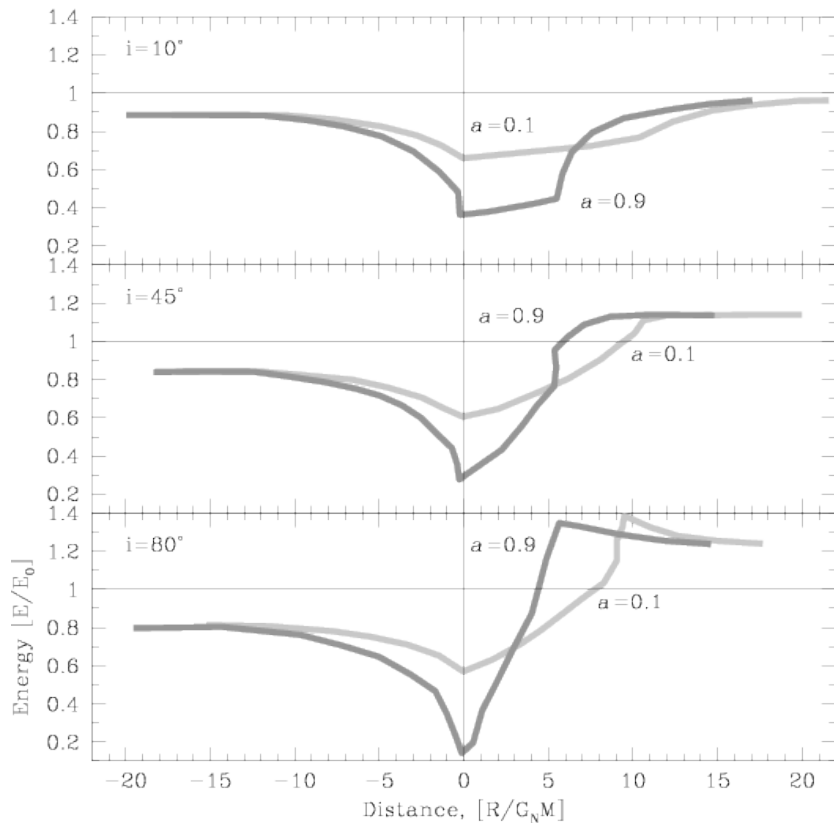
A moving caustic makes the line profile variable in time.

An example for $a=0.9$ and $i=45^\circ$



Red/blue edges of the emission
(set by the intersection of the line of nodes of the disk with the caustics).
Their position can be measured from observations.

Line “edge” profile revealed by microlensing



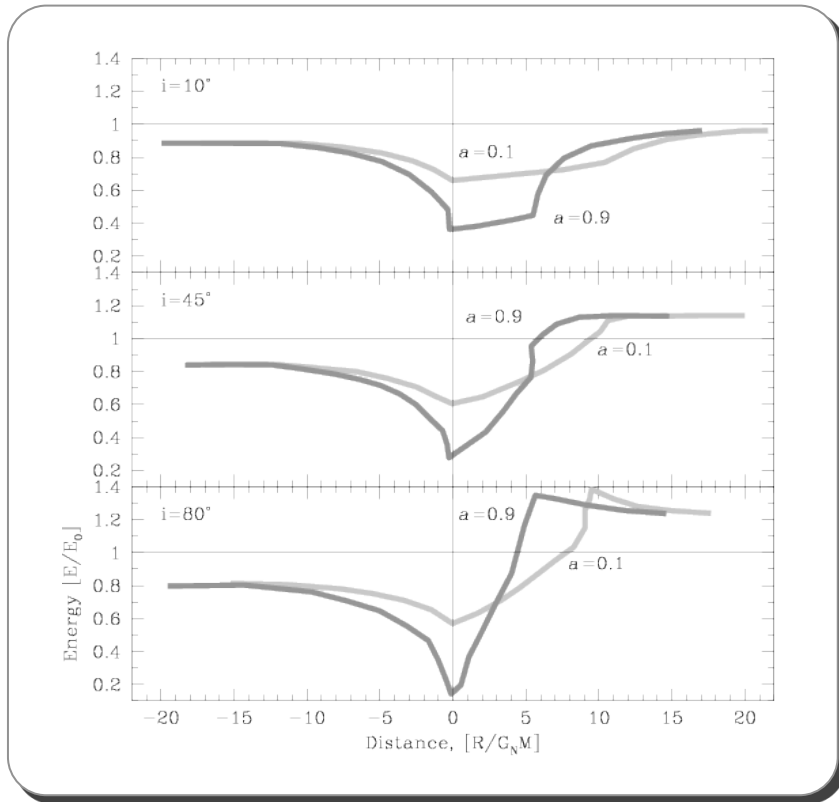
The key information be extracted from the temporal evolution of red/blue edges of the “portrait”.

The scaling of the X axis (time/distance) depends on the projected velocity of the caustic with respect to the disk line of nodes.

However, the evolution (curve shape) is governed only by (1) the disk inclination angle i and (2) the black hole momentum a .

It does not depend on numerous additional parameters, describing the system harboring the black hole, the accretion disk or the X-ray source illuminating it.

Universality of the “edge” profiles



The universality of the profiles can be demonstrated with a Newtonian toy model.

Keplerian velocity

$$v_K = \sqrt{\frac{G_N M}{r}}$$

Caustic's velocity w.r.t. the line of nodes

$$r(t) = v_c t \cos \alpha_c$$



Doppler red/blue shift

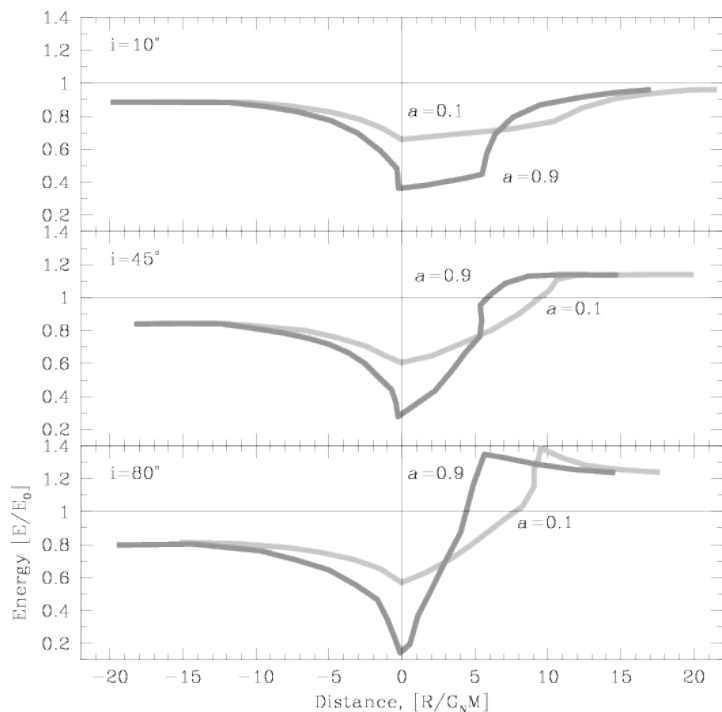
$$g(t) = \pm \sqrt{\frac{G_N M \cos^2 i}{v_c \cos \alpha}} \sqrt{\frac{1}{t}}$$

Here the shape of the $g(t)$ evolution is given only by \sqrt{t} and does not depend on the other parameters.

For example, a change in the caustic velocity would lead only to stretching/squeezing of the X axis. The black hole mass has the same effect as it changes the natural scale – R_g .

Description within GR introduces only technical complication, but does not change this qualitative picture.

“Edge” profile properties



Fitting of these “edge profiles” to the data may allow to determine the black momentum / disk orientation.

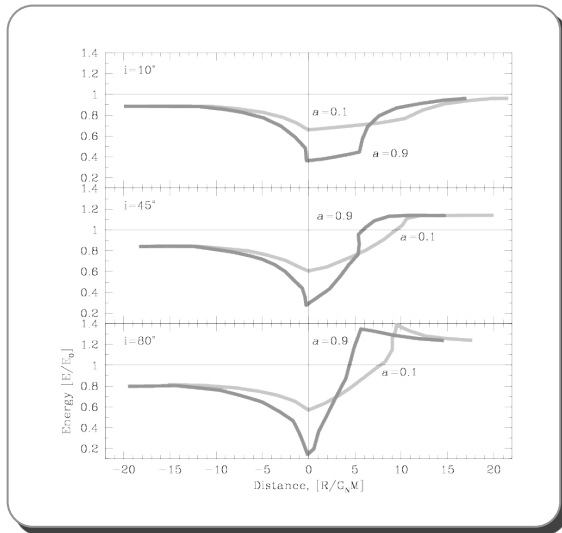
More interestingly, if the quality of the data is sufficient, a measurement of the edge profile can be used for testing the relativistic gravity theory.

A face-on disk: (1) the left/right part of the curve are symmetric. (2) the measurement of $g(t)$ gives the gravitational redshift as a function of time. (3) a “plateau” is created as the caustic crosses the ISCO.

Inclined disk: (1) the left/right parts are not symmetric – Doppler shift. (2) “plateau” is tilted.

Inclined disk, $a > 0$: the “plateau” is deformed due to the frame dragging effect

Celestial mechanics around a black hole



The measurements of evolution of the red/blue edges may provide a unique possibility to characterise the gravity close to the black hole horizon.

Measurements of the “microlensing portraits” would lead, in some sense, to “Kepler laws” in the strong-field limit, enabling the study of the “celestial mechanics” in the event horizon vicinity.

The most straightforward application is to the 6.4 keV Fe K α lines, observed in a lensed AGN (e.g. RX J1131-1231). Moreover, Chartas+ '12 already reported the energy shift of Fe K α in this source, presumably due to microlensing.

The typical duration of one of such microlensing events is expected to be ~ 1 month and there should be several of them per decade. \rightarrow This requires a dedicated monitoring campaign.

This method can already be used with the current generation of X-ray instruments, providing the unique constraints on the relativistic gravity in the strong-field regime.