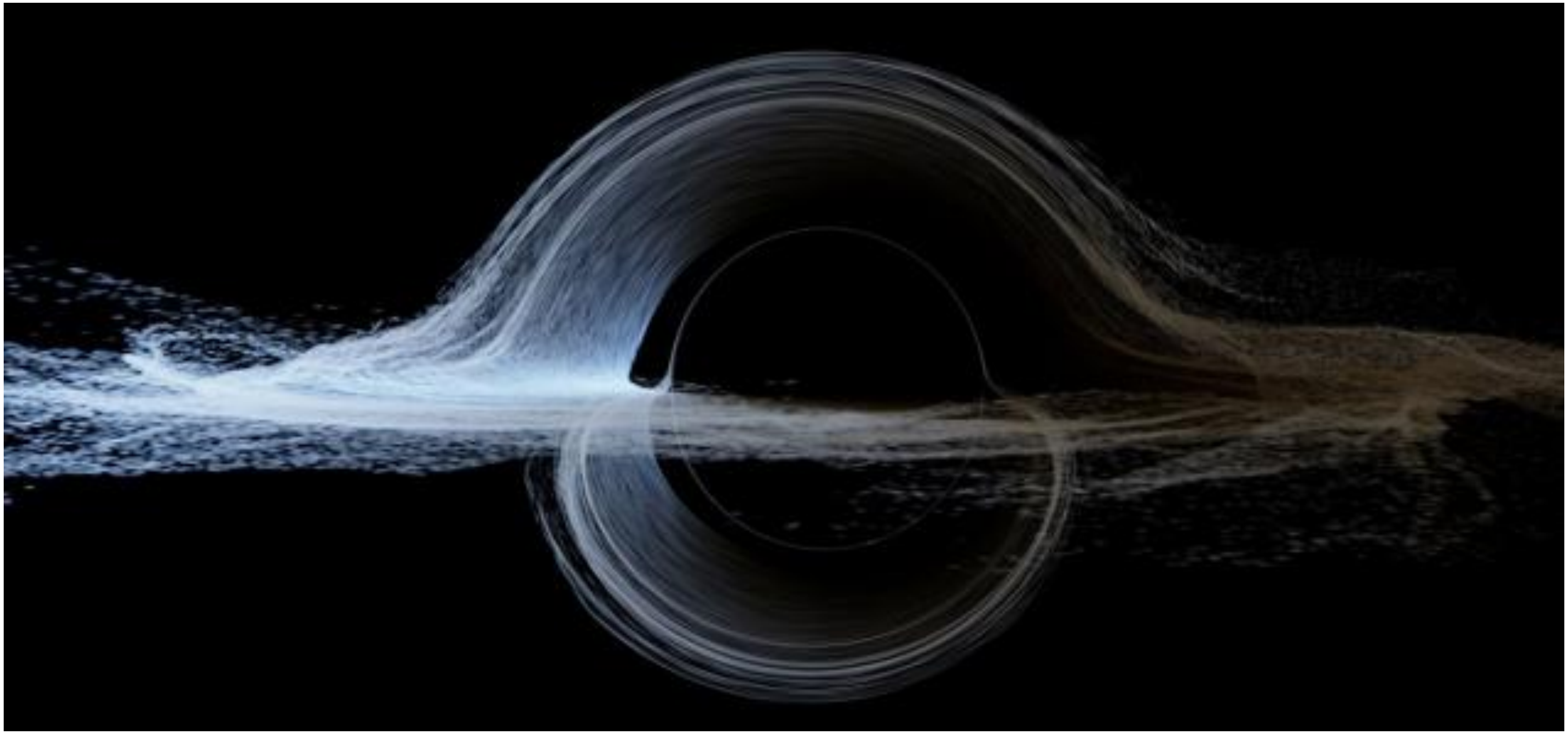
Measuring the Innermost Stable Circular Orbits of Supermassive Black Holes



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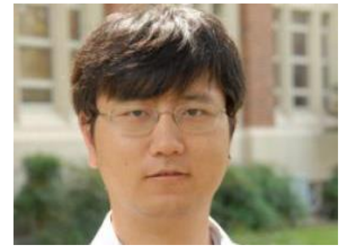

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Dissecting an Accretion Disk

- Direct imaging of accretion
- Indirect Mapping Methods

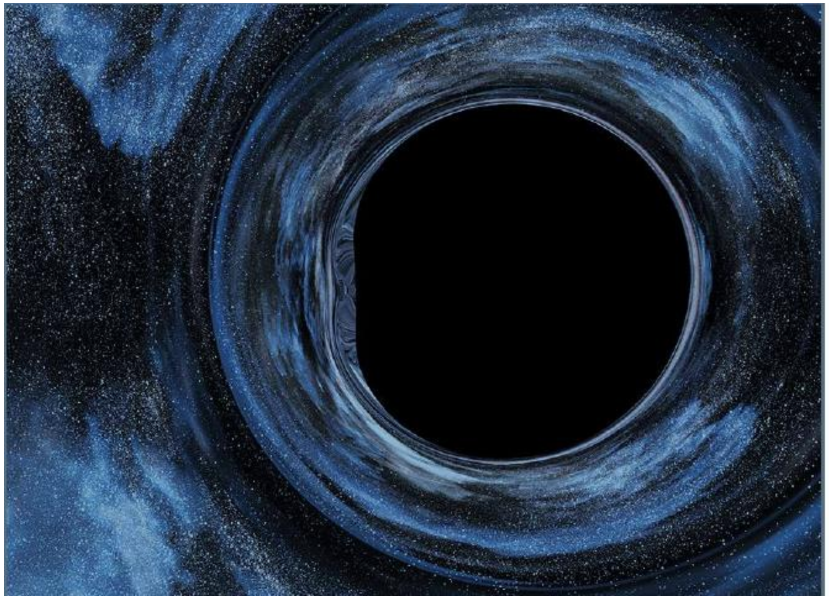
(a) Light travel time arguments

(b) Reverberation Mapping of the Broad Line Region

(a) Microlensing of the Continuum Emission from the Accretion Disk

(b) Microlensing of Fluorescent Emission Lines from the Accretion Disk

Imaging a Black Hole



Credit: Kip Thorne

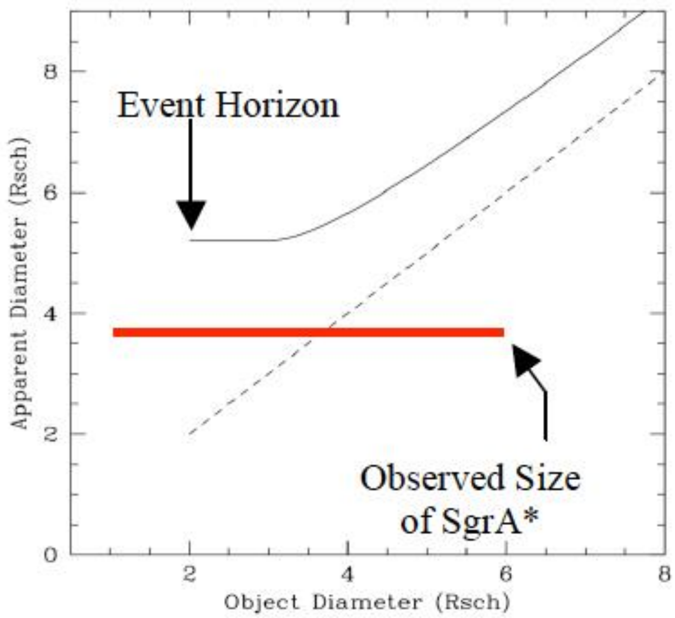
A fast-spinning black hole (left) moving in front of the star field shown on the right (courtesy of Kip Thorne and the Double Negative visual-effects team).

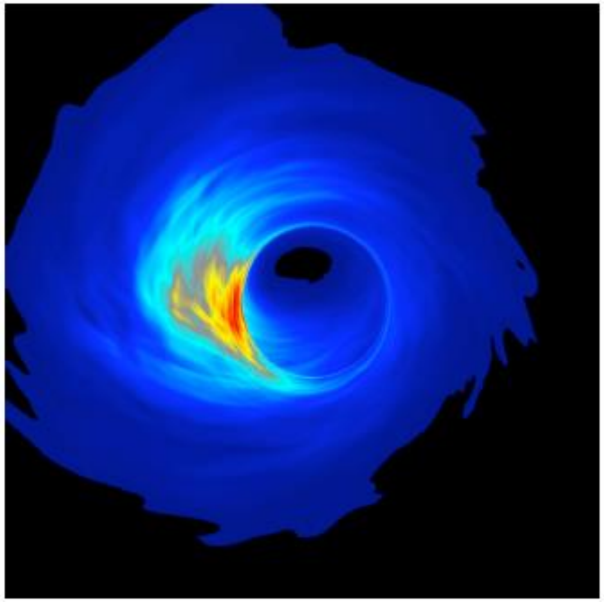
Light rays from the background stars are gravitationally lensed.

The **dark silhouette of a black holes' event horizon** is more than doubled in apparent size thanks to the bending of light rays by the hole's gravity. Sgr A*'s horizon will appear to span a mere ~55 microarcseconds

Imaging Sgr A*

Because of gravitational lensing a black hole will appear larger than its true diameter.





Credit: Doeleman et al. 2008

Sgr A* was observed in April 2007 using a three station VLBI array (ARO/SMT, CARMA, JCMT) at a wavelength of 1.3mm (Doeleman et al. 2008).
Solid line for non-spinning black hole + lensing, dashed line no lensing effects.
The observed size is smaller than the minimum apparent size.
This can be explained by compact emission from the approaching side of an accretion disk.

Dissecting an Accretion Disk with Microlensing

Direct imaging of quasars using submm VLBI is not possible due to their large distances. Microlensing, however, can resolve:

Structure of AGN Accretion Disks

- The sizes of the Optical and UV regions of AGN
- Comparison with Thin Disk Theory
- **Use the distribution of shifts of the Fe line to infer the ISCO, *a*, and *i***

Structure of AGN Coronae

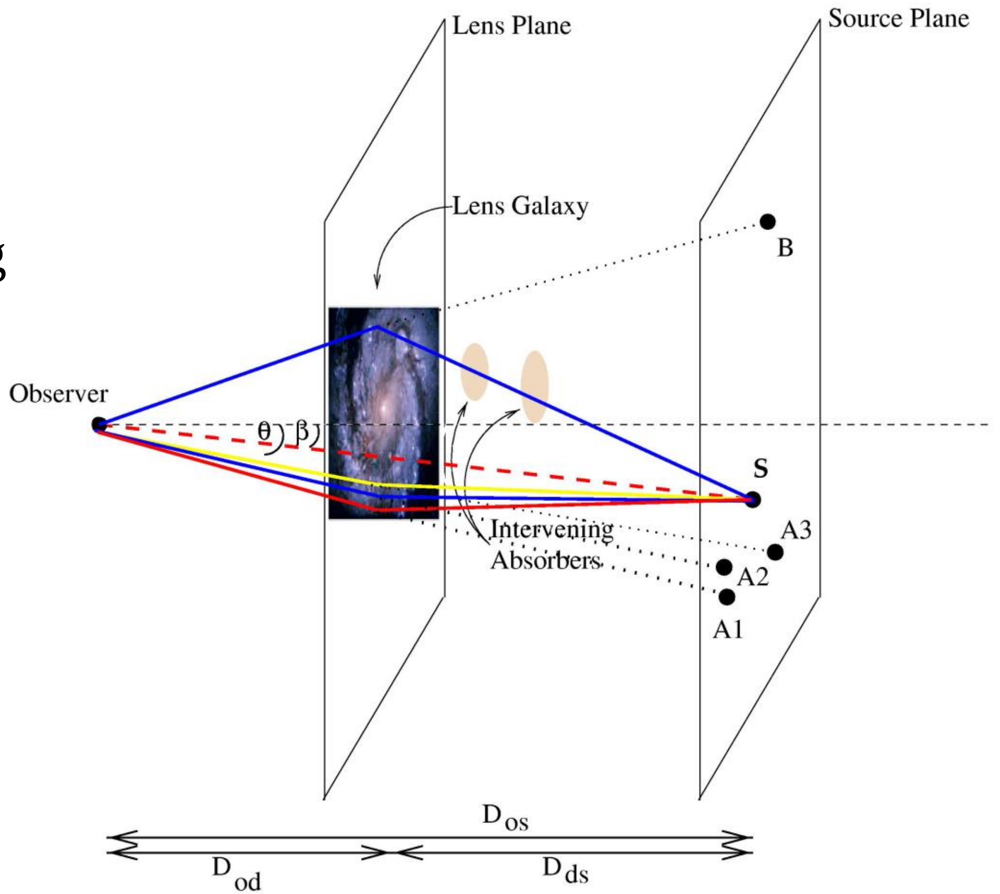
- The sizes of X-ray emitting coronae of AGN

Dissecting an accretion disk with microlensing

Microlensing is the bending of light produced by the individual stars in the lensing galaxy.

Microlensing variability occurs when the complex pattern of caustics produced by stars in the lens moves across the source plane.

The characteristic scale of these caustic patterns is the **Einstein radius.**



Conceptual diagram of the deflection of light in a 4 image gravitational lens system.

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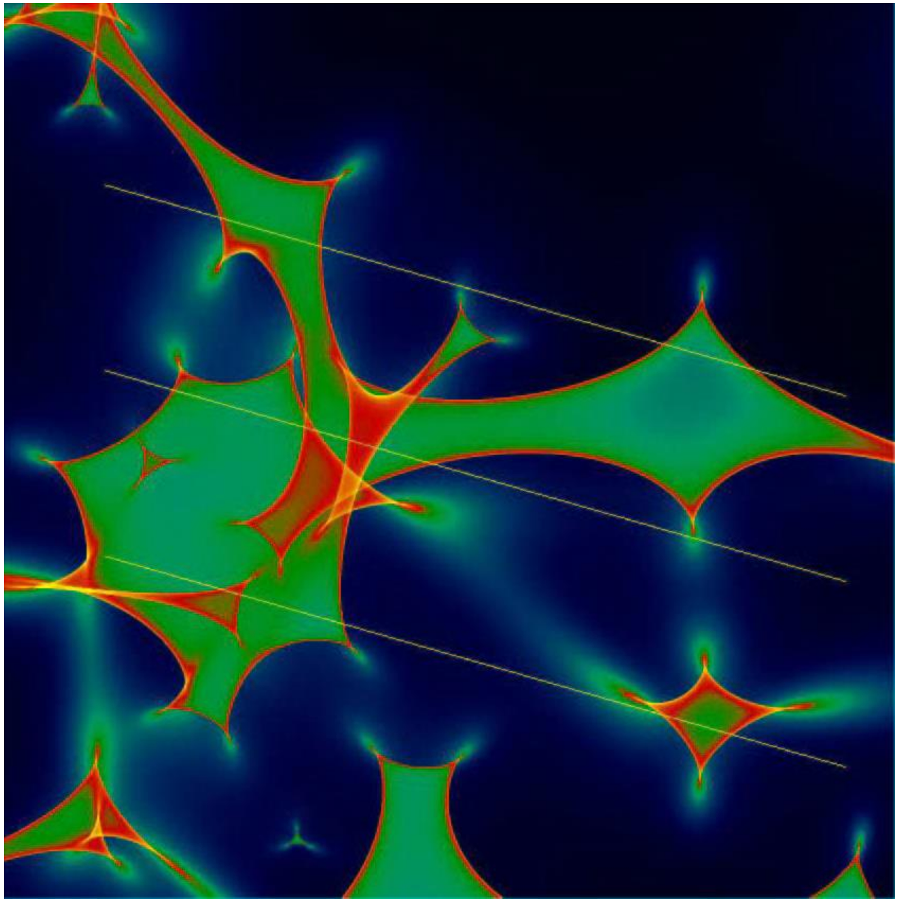
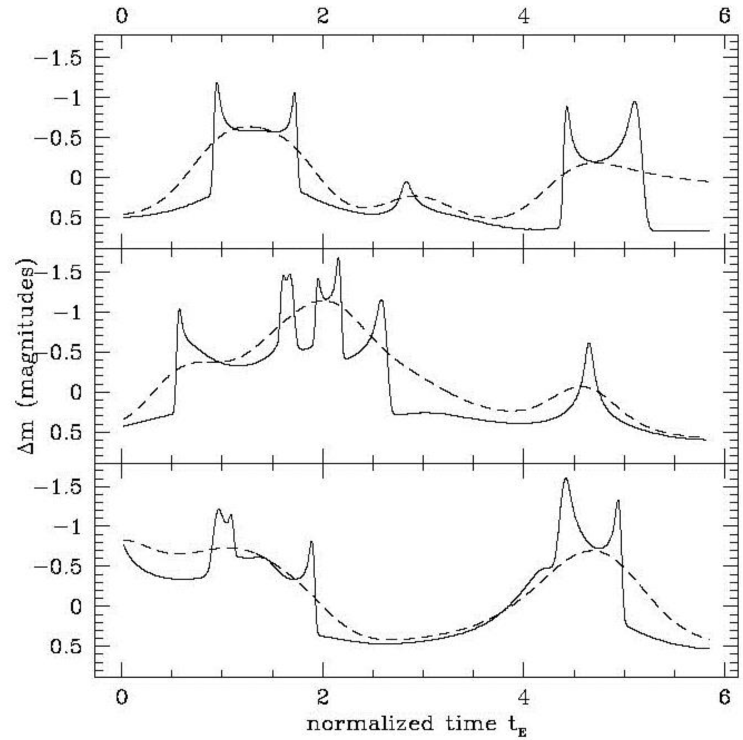
Dissecting an Accretion Disk with Microlensing

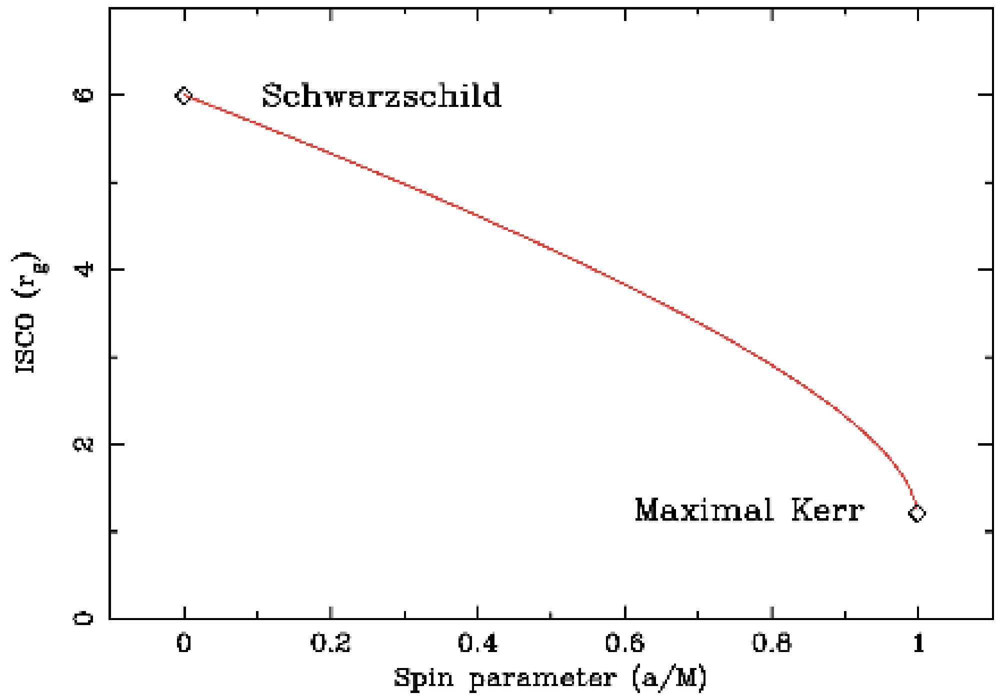




Figures from J. Wambsganns, Gravitational Lensing in Astronomy

Simulated magnification pattern in the source plane, produced by a dense field of stars in the lensing galaxy. Simulation applies to image A of Q2237+0305.

ISCO and Size of Accretion Disk at Wavelength λ



Thin accretion disk theory predicts that the characteristic size of the accretion disk at wavelength λ scales as

$$R_\lambda = \left(9.7\times 10^{15}\right)\left(\lambda/\mu m\right)^{4/3}\left(M_{BH}/10^{9}M_{solar}\right)^{2/3}\left(L/\eta L_E\right)^{1/3} cm$$

and the disk temperature scales as: $T_{eff} \propto r^{-\beta},\ \beta = 3/4$

Dissecting an Accretion Disk with Microlensing

Microlensing Model

- The main free parameters of a microlensing model are :

- the scale lengths of the emission regions,
- a microlens mass scale,
- a mass fraction of the local surface density comprised of stars, and
- a velocity vector describing the motion of the AGN regions across the microlensing caustics.

- The microlensing analysis includes the creation of many random realization of the star fields near each image and the generation of magnification maps.

- Dynamic Microlensing

- Simulations that allow for movement of the stars between epochs also provide constraints on the inclination of the accretion disk and the direction of motion of the caustics

Dissecting an Accretion Disk with Microlensing

- We are performing multiwavelength monitoring of several quasars :

RX J1131-1231 ($z_s = 0.66$, $z_l = 0.30$)
Q J0158-4325 ($z_s = 1.29$, $z_l = 0.317$)
SDSS0924+0219 ($z_s = 1.524$, $z_l = 0.39$)
Q 2237+030 ($z_s = 1.60$, $z_l = 0.04$)
HE 0435-1223 ($z_s = 1.689$, $z_l = 0.46$)
PG 1115+080 ($z_s = 1.72$, $z_l = 0.31$)
SDSS1004+4112 ($z_s = 1.734$, $z_l = 0.68$)
QSO 1104-1805 ($z_s = 2.32$, $z_l = 0.73$)

with the main scientific goal of measuring the emission structure near the black holes in the optical\UV and X-ray bands in order to test accretion disk models.

- X-ray monitoring observations were performed with *Chandra*
- *Optical* (*B*, *R* and *I* band) observations were made with the SMARTS Consortium 1.3m telescope in Chile.

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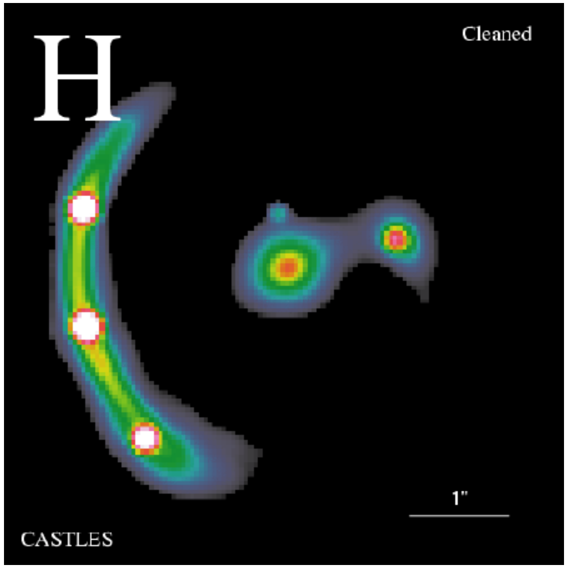
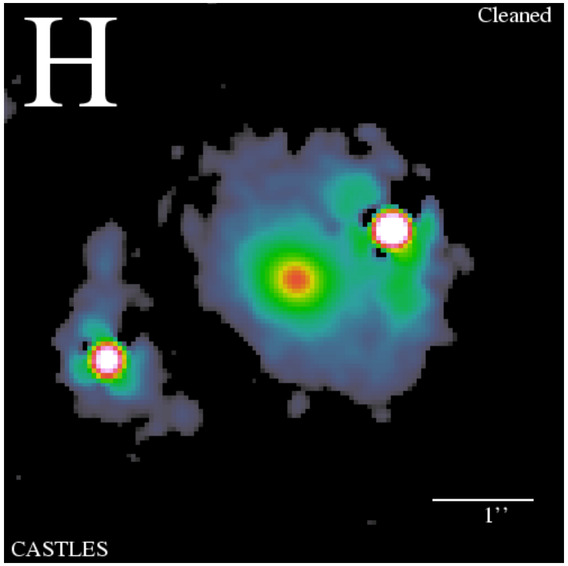
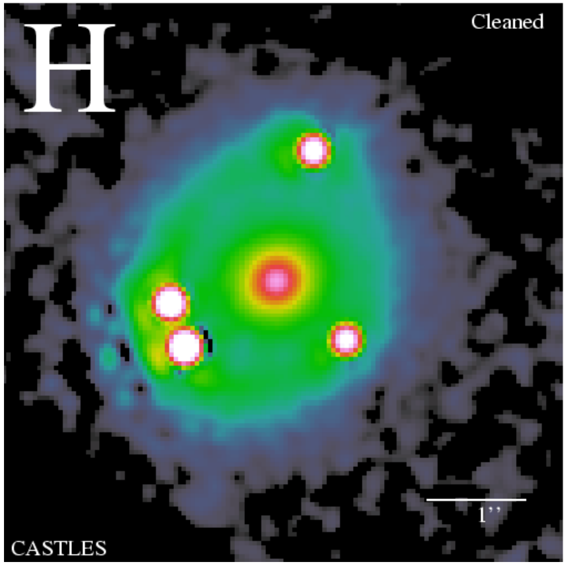
Dissecting an Accretion Disk with Microlensing







A HST image of quasar
RX J1131-1231
z_s = 0.658, z_l=0.295

A HST image of quasar
HE 1104-1805
z_s = 2.32 , z_l = 0.73

A HST image of quasar
PG 1115 +080
z_s = 1.72 , z_l = 0.31

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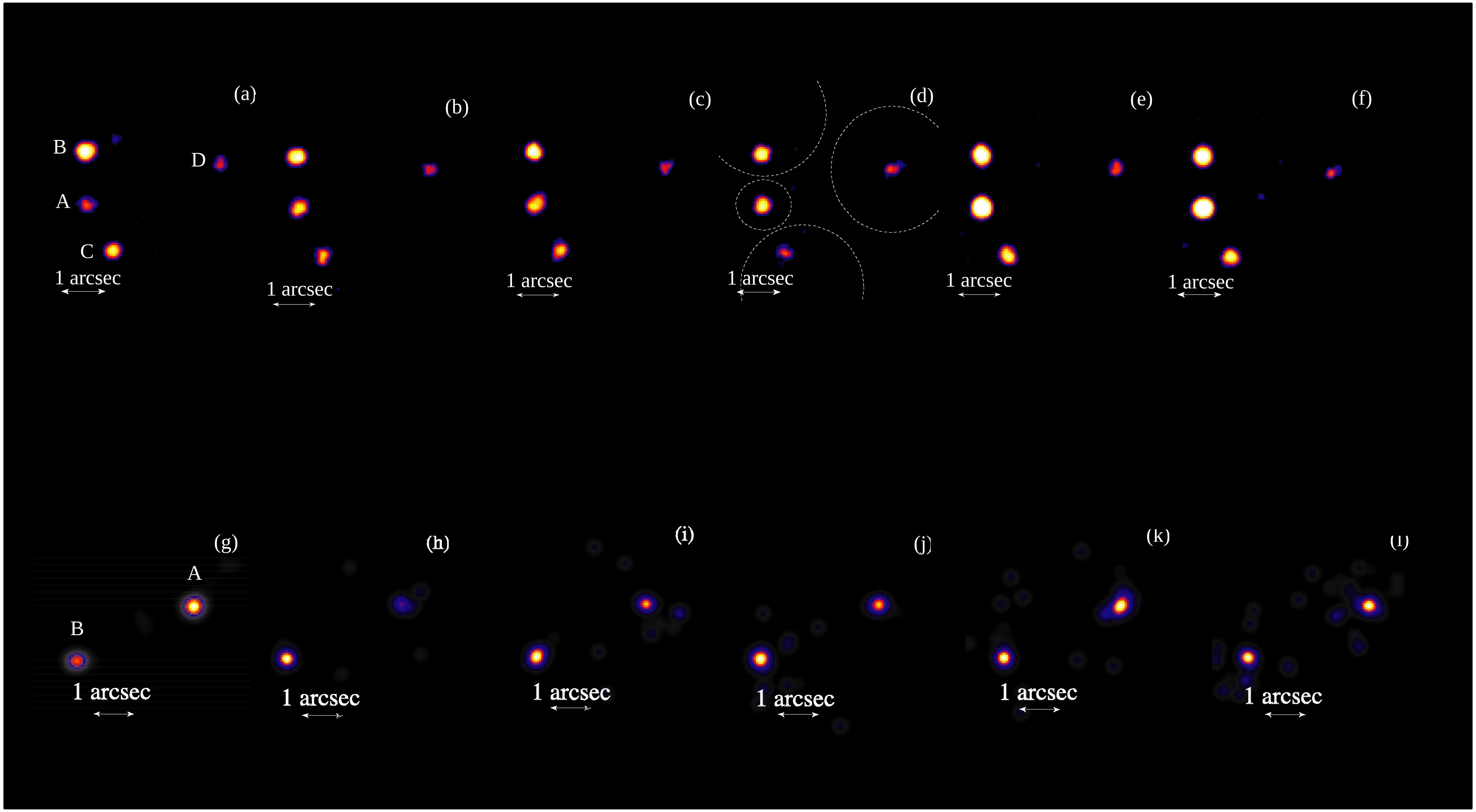
Dissecting an Accretion Disk with Microlensing



Images in the 0.2 - 10 keV bandpass of the *Chandra* observations of RX J1131-1231 and HE 1104-1805.

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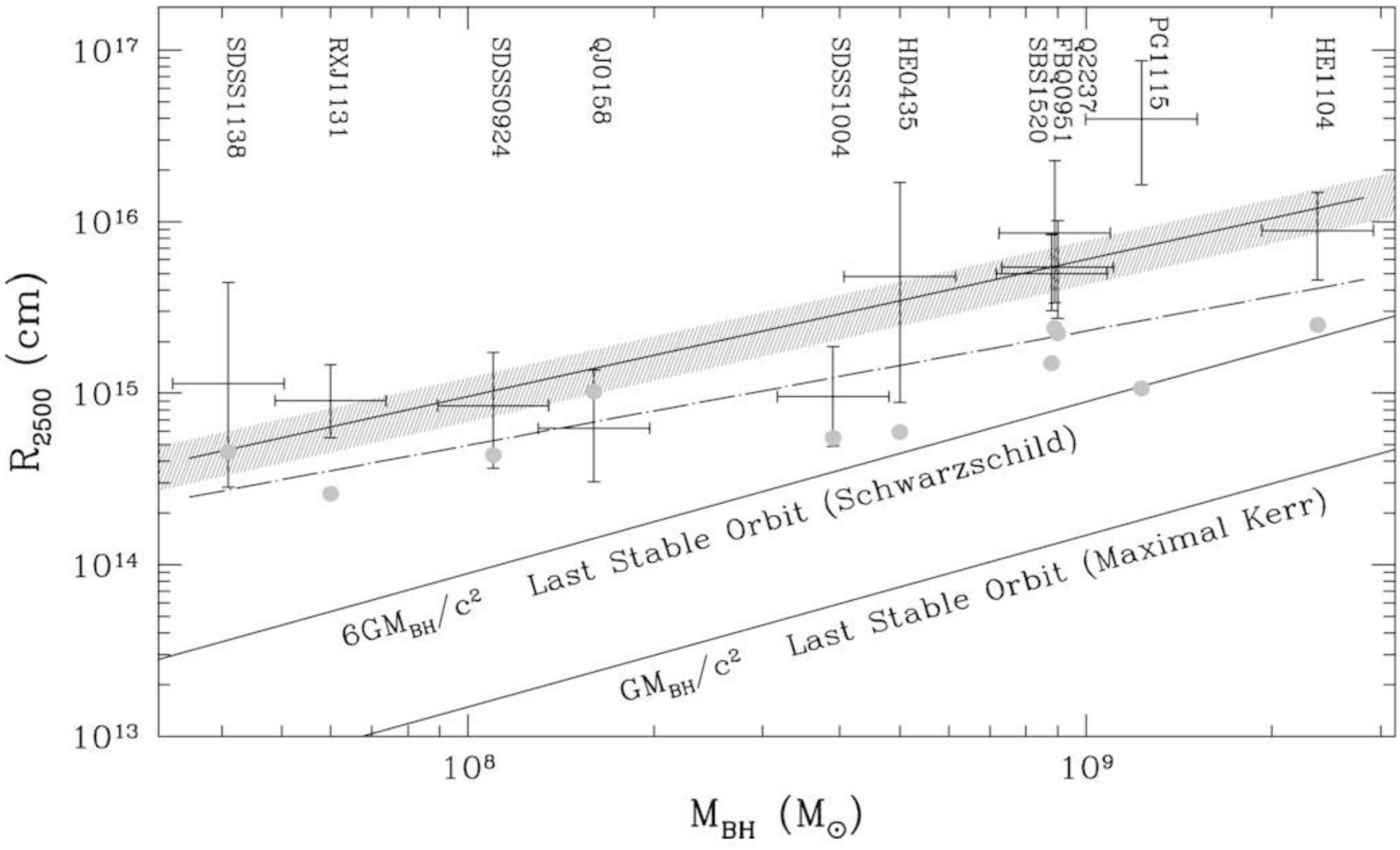
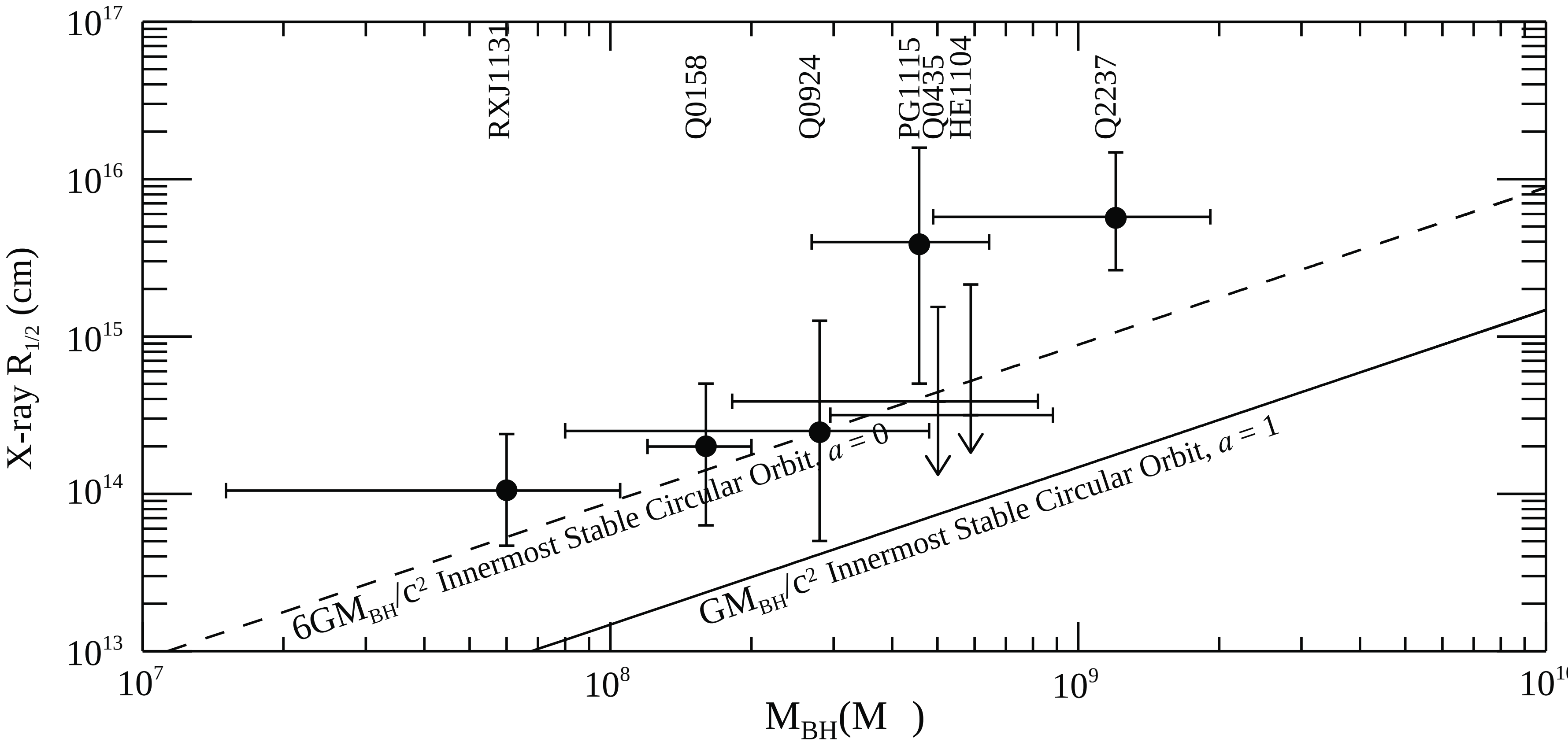


The Quasar Accretion Disk Size versus Black Hole Mass

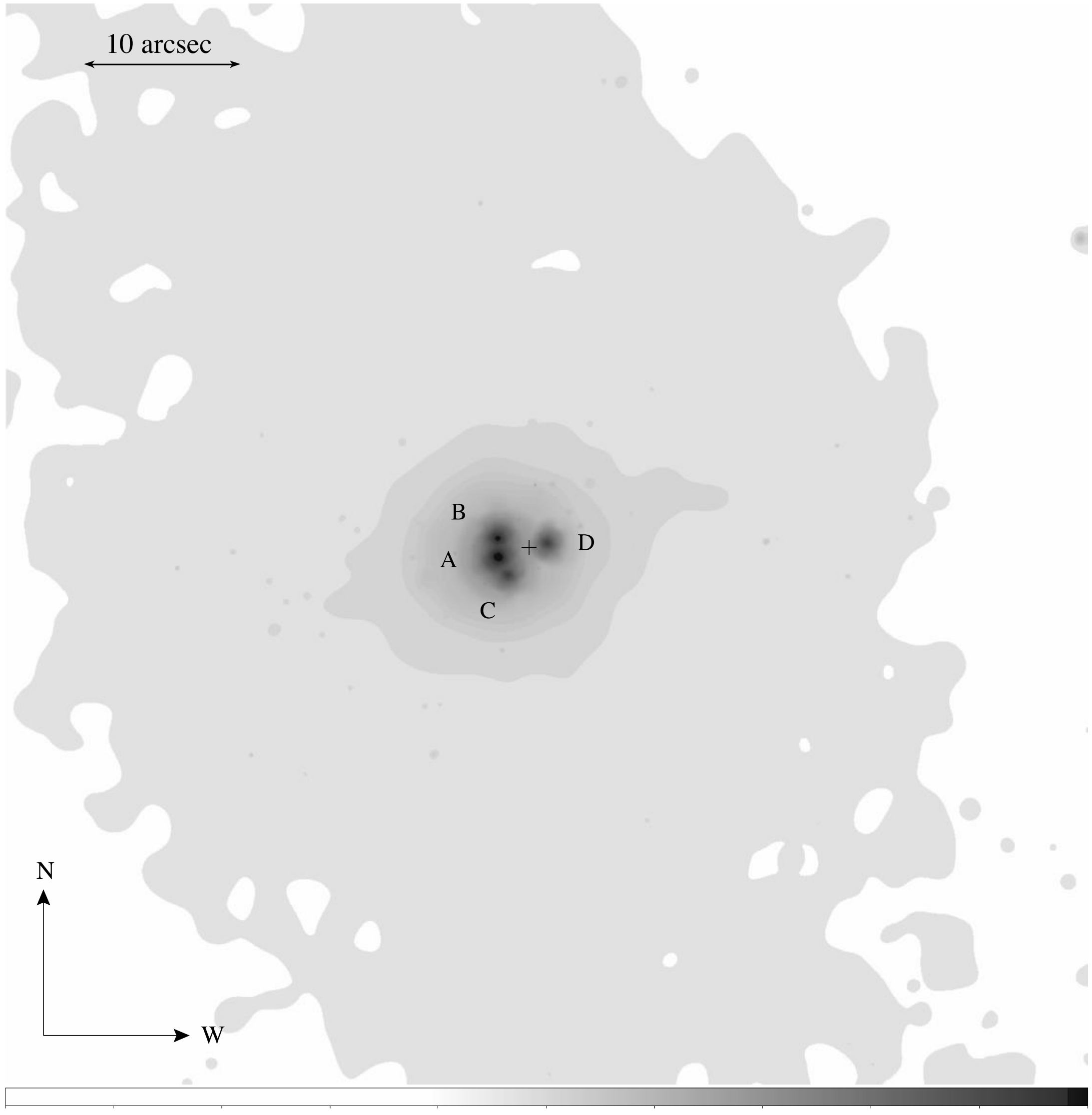
Morgan et al. 2010



X-ray half-light radii of quasars as determined from our microlensing analysis versus their black hole masses.

Chartas et al. 2015

Structure of $z = 0.66$ quasar RX J1131-1231



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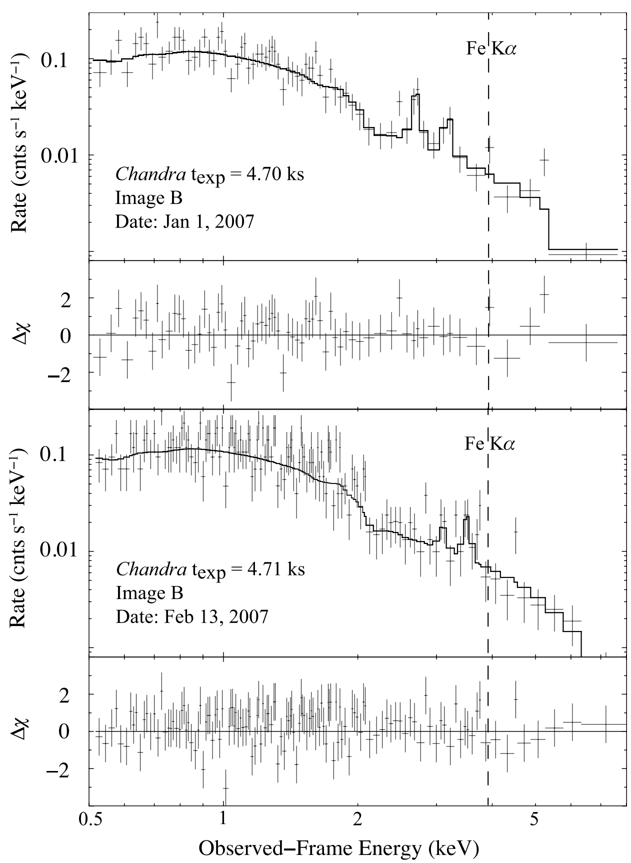
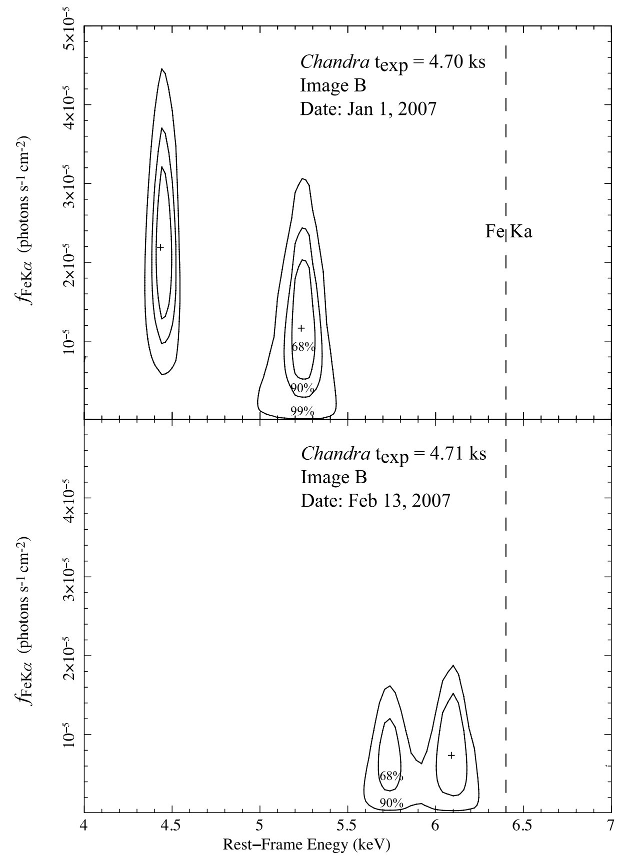
Structure of $z = 0.66$ quasar RX J1131-1231

RX J1131−1231 has been monitored 38 times over a period of 10 years with the Chandra X-ray Observatory. As reported in Chartas el al. 2012, redshifted and blueshifted Fe Ka lines have been detected in the spectra of the lensed images.





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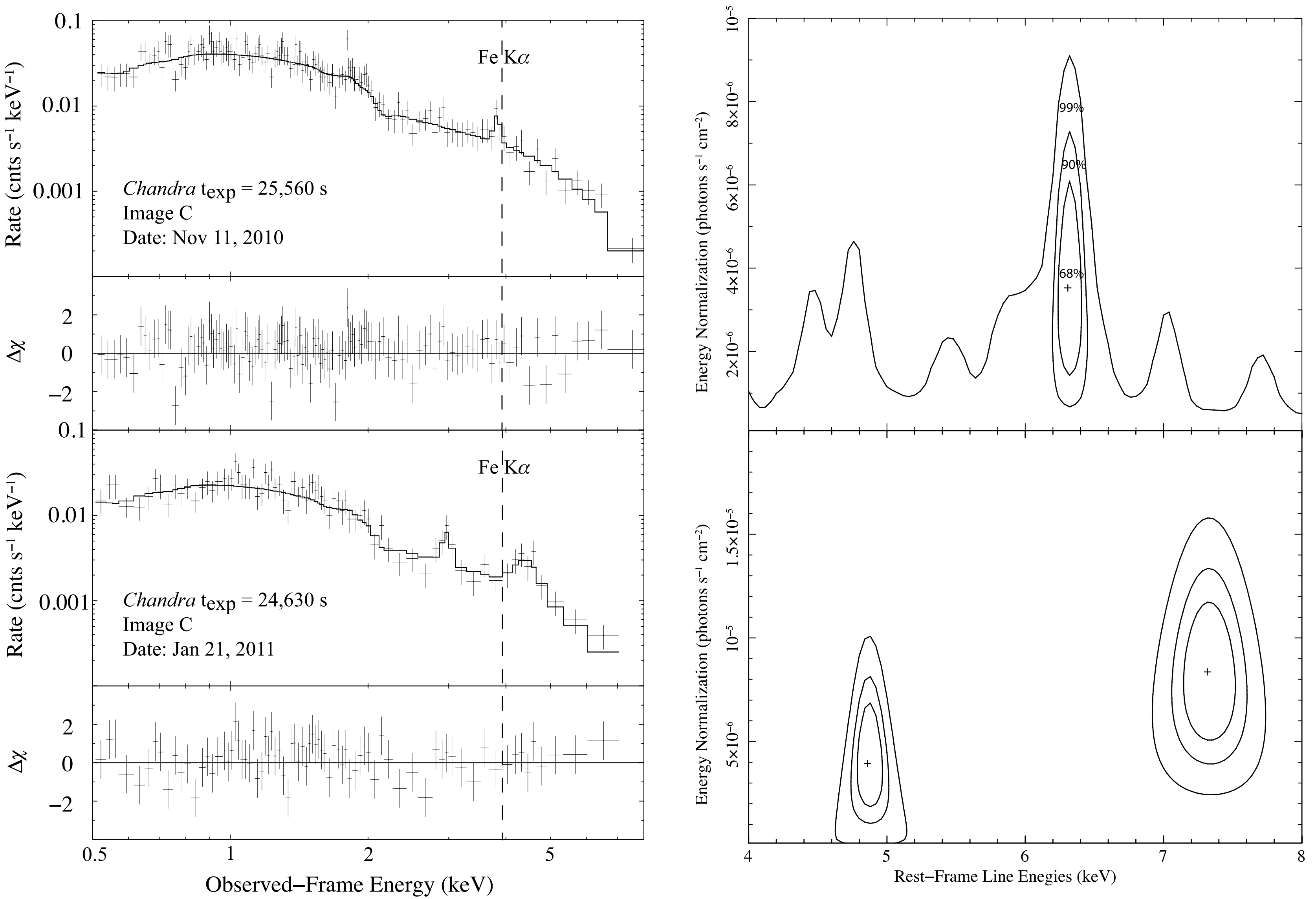
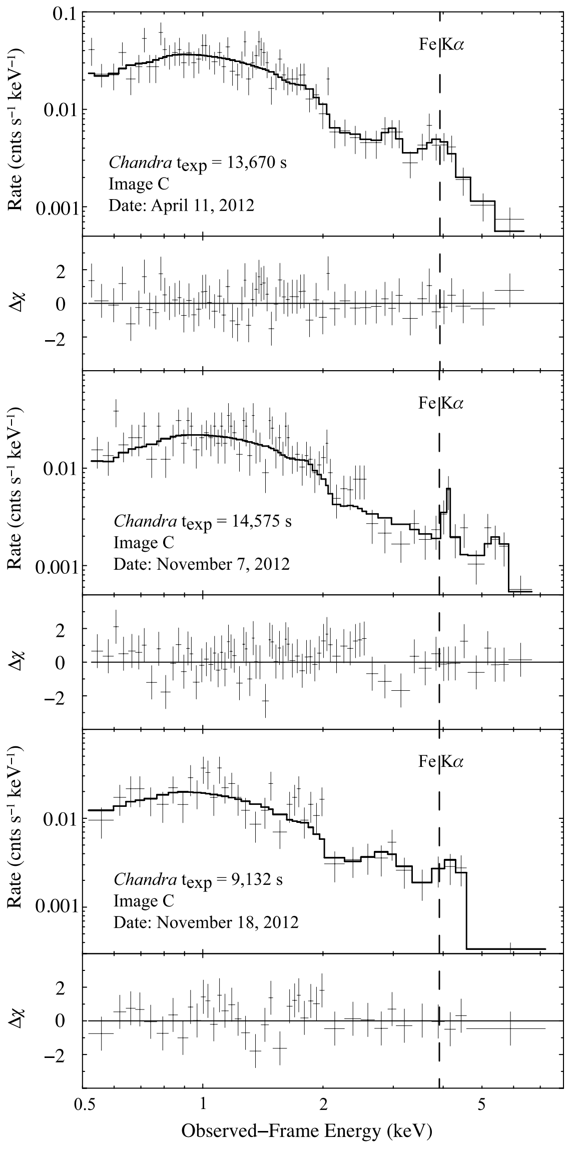
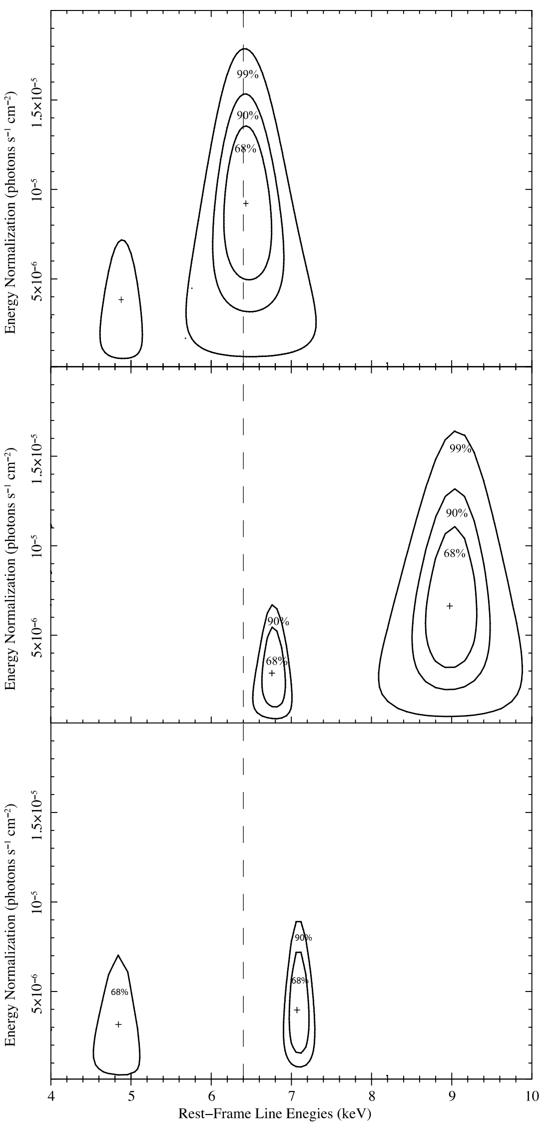
X-ray Microlensing of Fe Kα line in Image C of RX J1131



X-ray Microlensing of Fe Kα line in Image C of RX J1131





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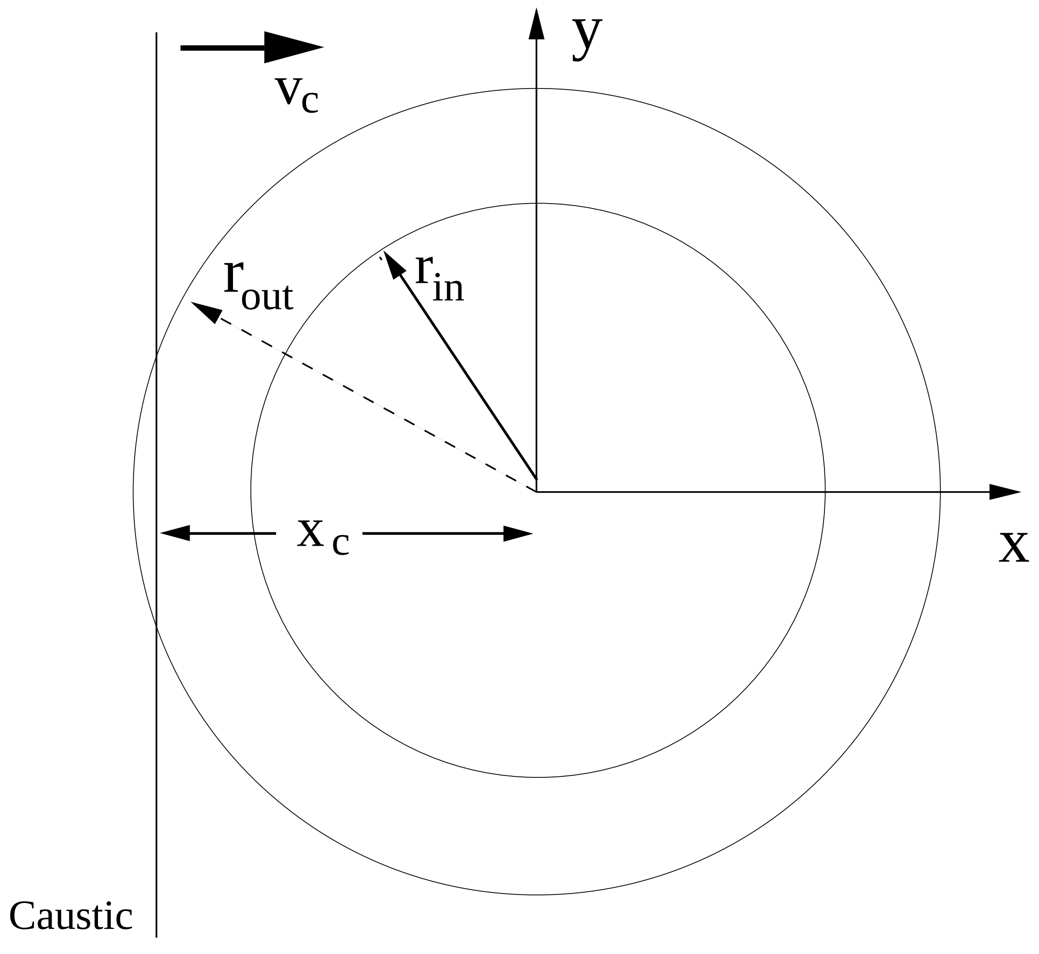
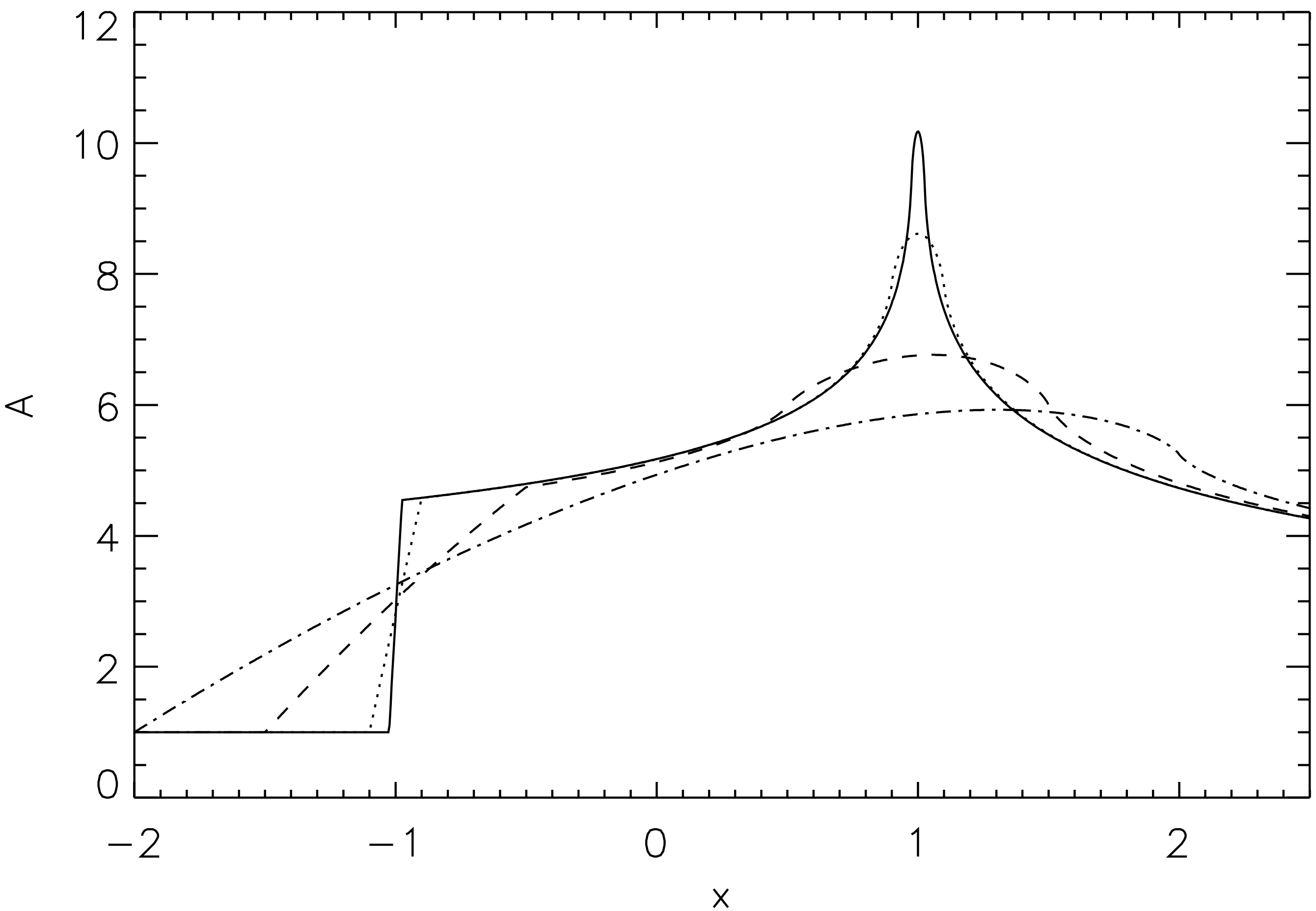
Individual Microlensing Events in RXJ 1131-1231



Caustic crossing an accretion disk (face-on case)

Individual Microlensing Events in RXJ 1131-1231



The amplification of the emission region of radius r=1 and thickness dr by a caustic as a function of the distance of the caustic from the center of the ring. The curves show dr/r = 0.025, 0.1, 0.5, 1 corresponding to solid, dotted, dashed, and dash-dot lines.

Generalized Doppler Shift

The observed energy of a photon emitted near the event horizon of supermassive black hole will be shifted with respect to the emitted rest-frame energy due to general relativistic and Doppler effects.

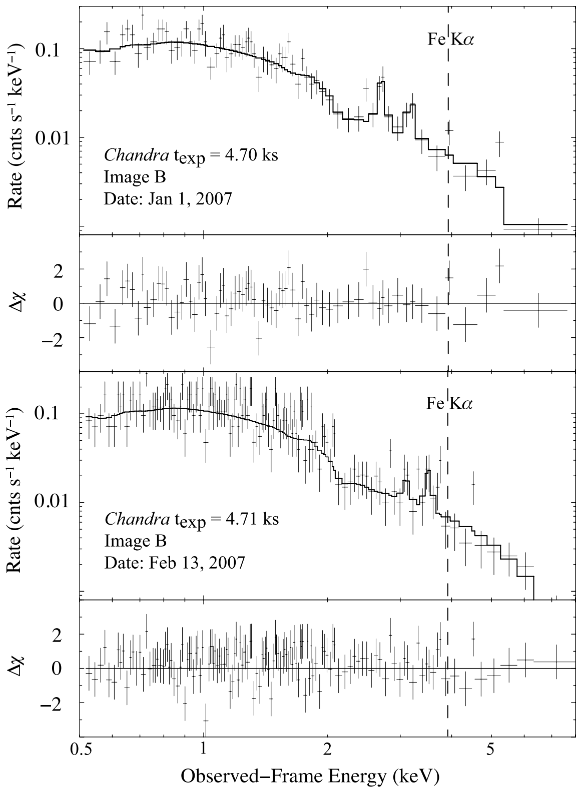
$$g = \frac{E_{obs}}{E_{emit}} = \delta\sqrt{\frac{\Sigma\Delta}{\mathrm{A}}}$$

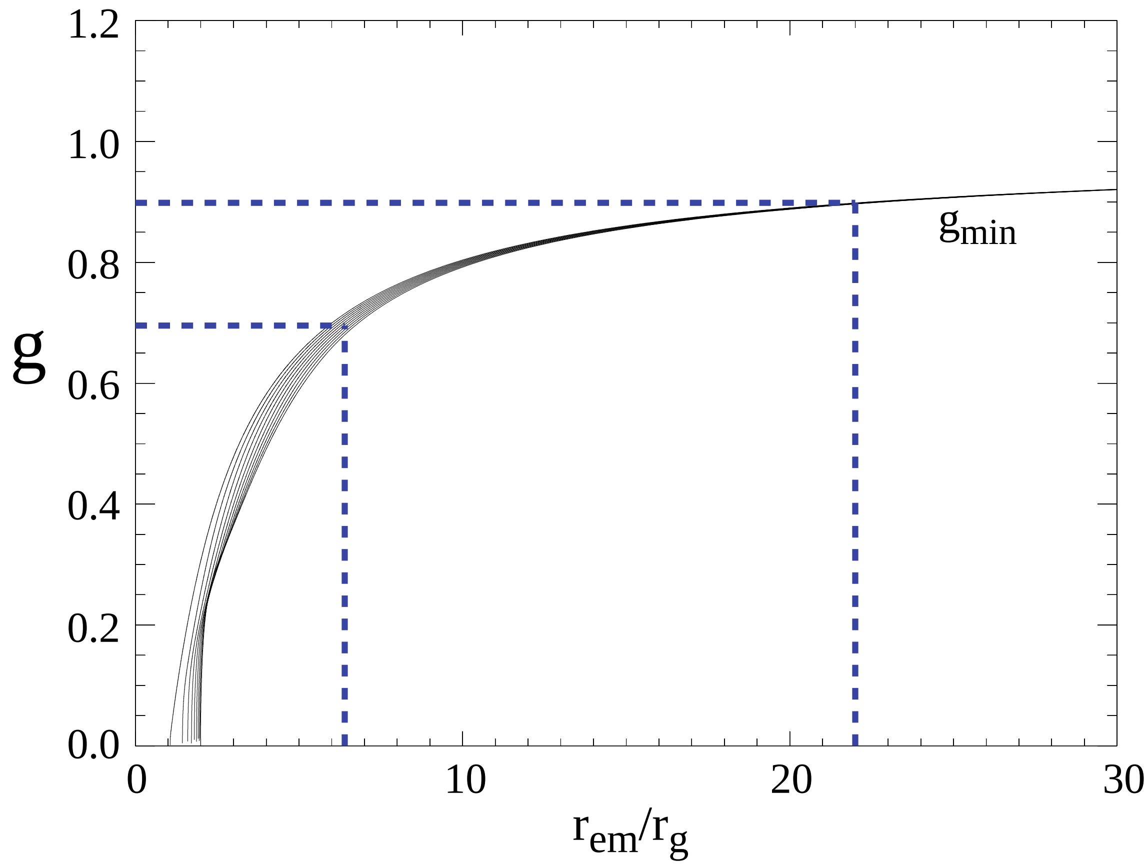
Where the Doppler shift is:

$d=\sqrt{\frac{1-v_f^2}{1-v_f\cos q_c}}$, where v_f is the azimuthal velocity and q_c is the angle between our line-of-sight and the direction of motion of the emitting plasma.

A, Σ, and Δ are defined as

$$A = \left(r^2 + a^2\right)^2 - a^2\Delta\sin^2\theta,\ \Sigma = r^2 + a^2\sin^2\theta,\ \Delta = r^2 - 2r_g r + a^2$$





Extremal shifts (g_{min}) of the Fe Kα line energy for spin values ranging between 0.1 and 0.998 in increments of 0.1. Horizontal dashed lines represent the observed values of the shifts $g=E_{obs}/E_{rest}$ of the most redshifted Fe Kα line components of the two epochs. The model can reproduce the observed shifts for i = 65°, and $\theta_{caustic}$ = 185°.

g-distribution method

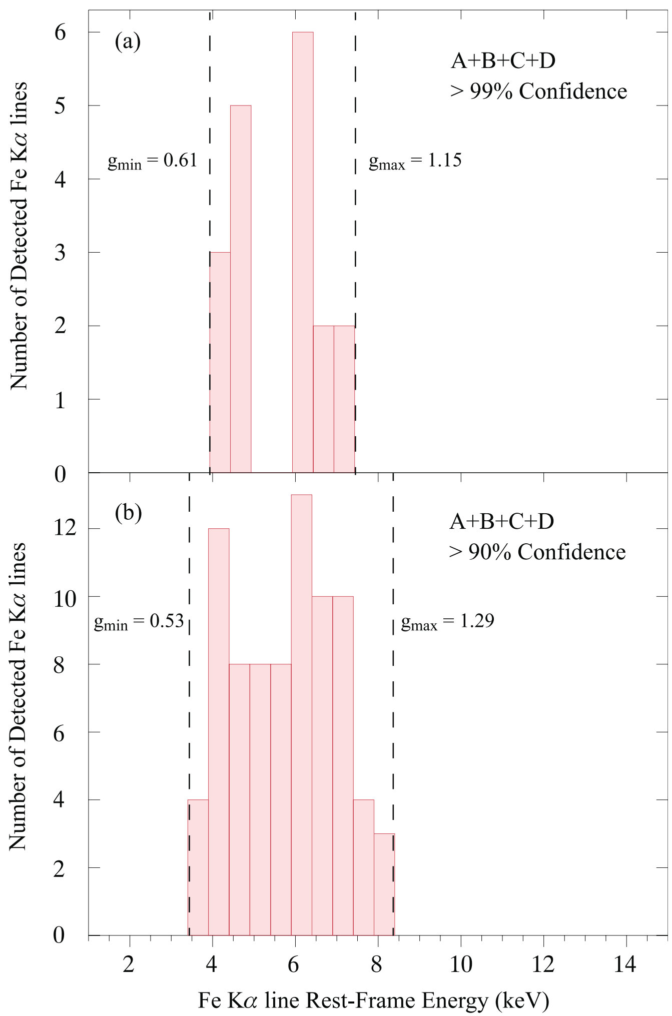
The value of ***g* will range between extremal values** that depend on the inclination angle *i*, the caustic angle θ_{caustic}, and the spin of the black hole.

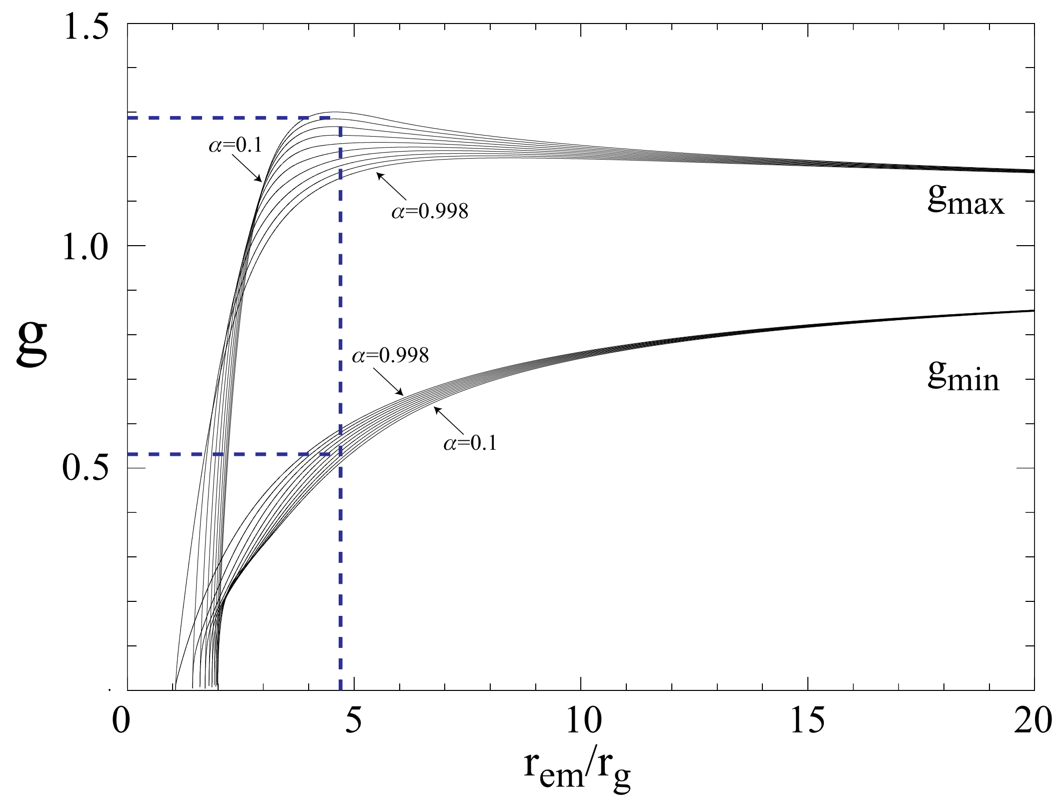
Triggering on a single microlensing event and monitoring the shifts of the Fe line during a single caustic crossing **is very difficult** from a practical sense.

The *g*-distribution method relies on determining the **distribution of Fe line shifts** from the spectra of individual lensed images obtained from a large number of X-ray observations.

The *g*-distribution is expected to show **sharp cut-offs**. The low energy cut-off is sensitive to the ISCO and the high energy cut-off is sensitive to the inclination angle.

g-distribution method





The cut-offs of the g-distribution constrain:

$i \approx 65^{\circ}$

$r_{ISCO} < 5r_g$

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Conclusions

- Using the microlensing method we find that the X-ray emitting **hot coronae of quasars have sizes of order 10r_g** and the **optical regions have sizes of order 100r_g**
- The sizes of the optical accretion disks of quasars as inferred from microlensing are 2-3 times larger than what is predicted by think disk theory
- The Fe Kα line varies in energy and strength during microlensing events. We use the **distribution of the Fe line shifts** to infer the inner most stable orbit, the inclination angle, and the spin of quasars.