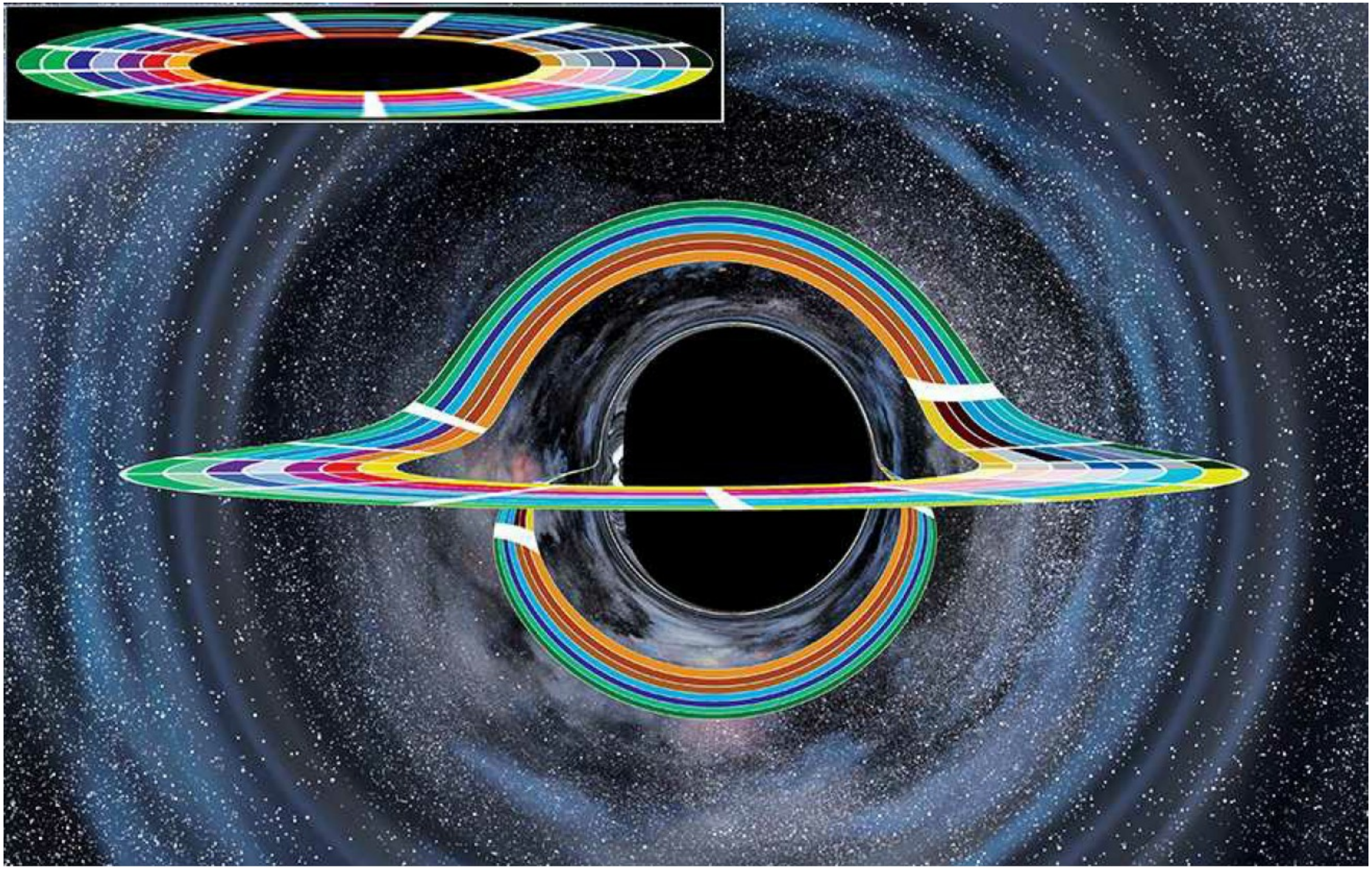
Size of the ISCO and Hot Corona from Gravitational Lensing



George Chartas in collaboration with: Henric Krawczynski, Xinyu Dai, Christopher Morgan, and Lukas Zalesky

X-ray Astronomy 2019, Bologna Italy

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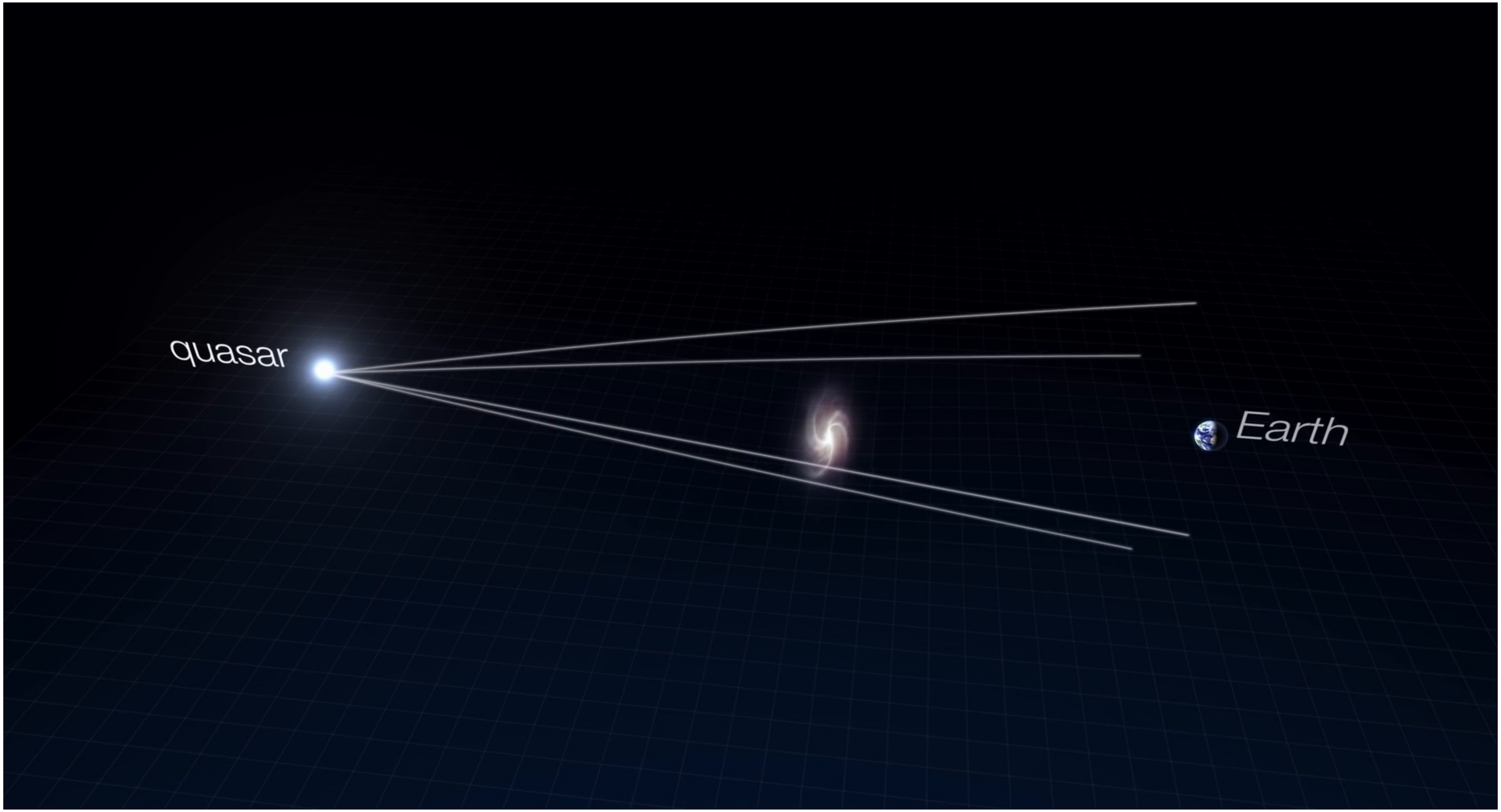
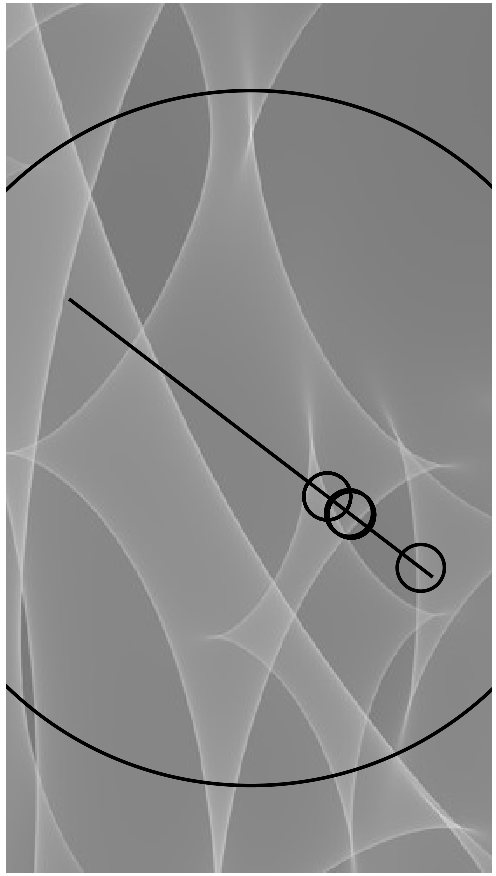
Outline

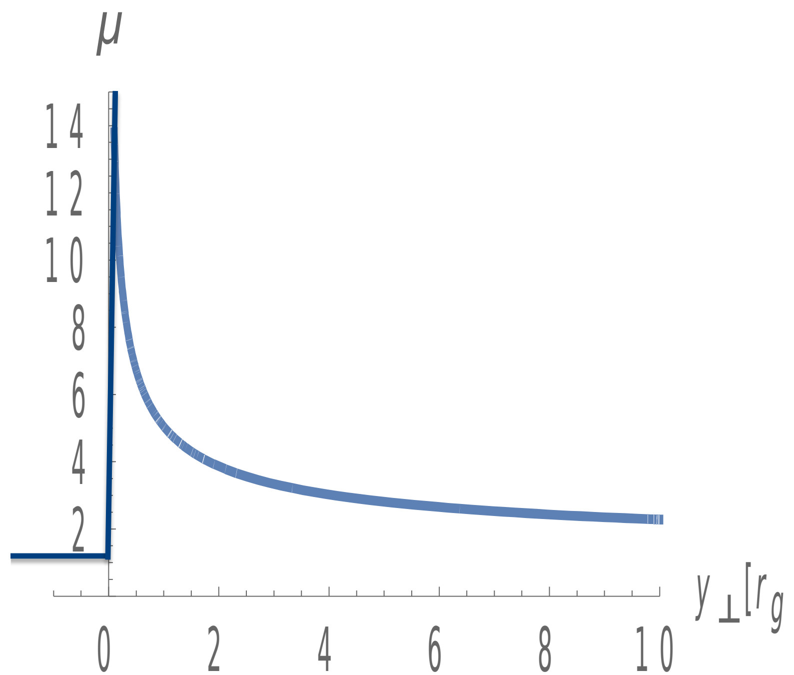
1. Quasar corona sizes from microlensing
2. Quasar ISCO and spin measurements from microlensing
3. Future prospects


quasar
Earth

Magnification Caustics



Simulated magnification map of image B of RXJ 1131 (Dai et al. 2010)



Magnification versus distance from caustic.

Characteristic timescales:

$$t_E = R_E / v_e \qquad t_S = R_S / v_e$$

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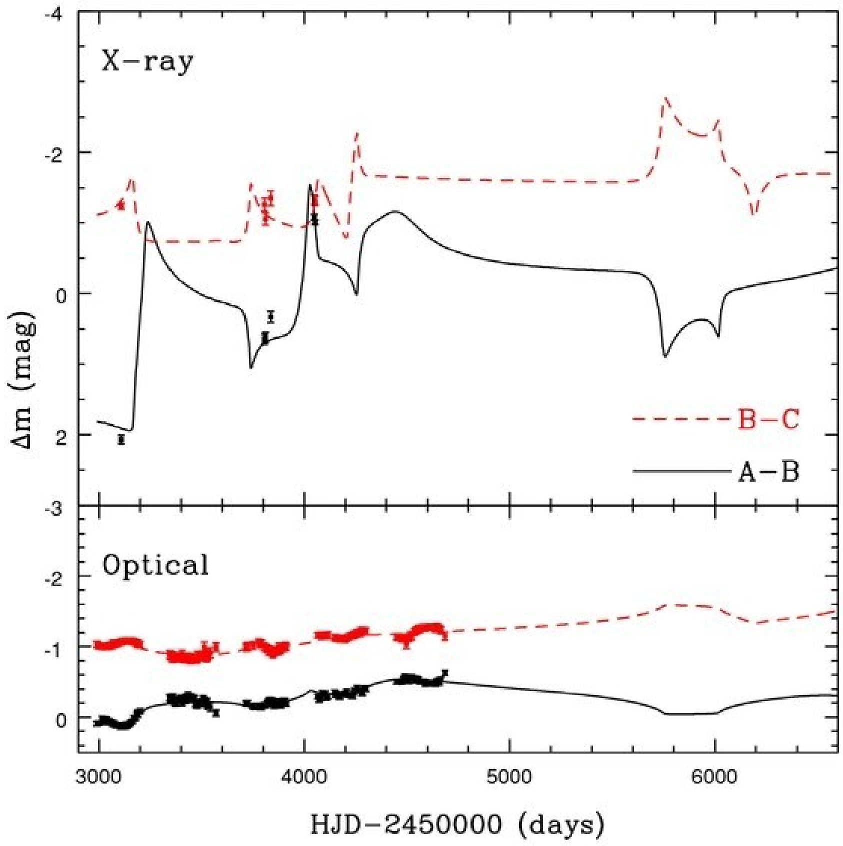
Microlensing Light-Curve Model

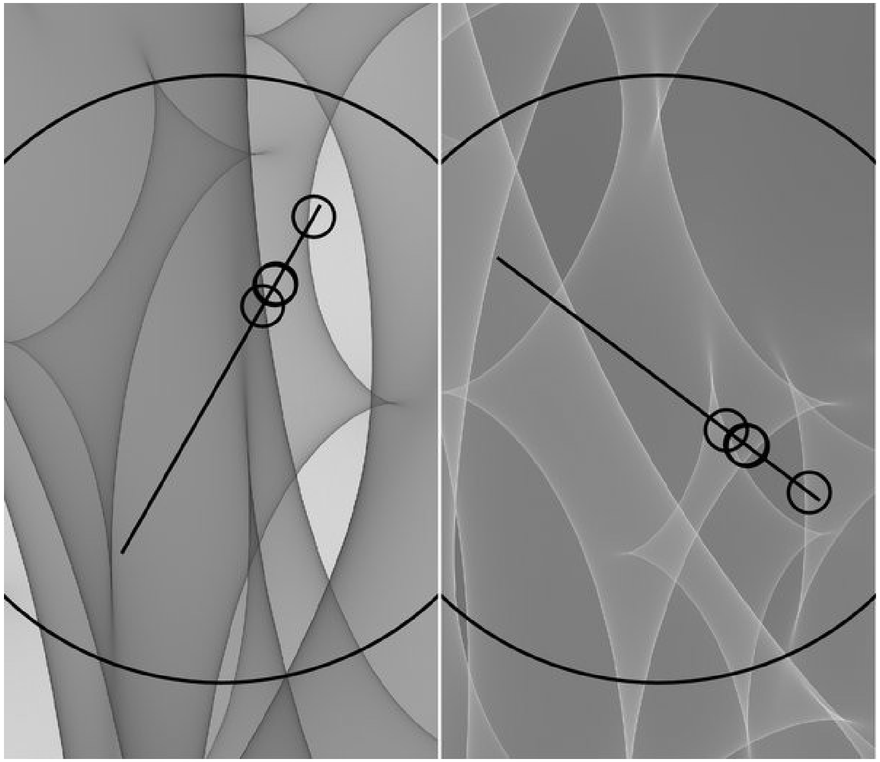
The main parameters of a microlensing model (Kochanek 2004) are:

- the sizes of the emission regions,
- the mass of the stars doing the microlensing,
- the fraction of normal matter to dark matter in the lensing galaxy
- the velocity describing the motion of the AGN regions across the microlensing caustics.
- The microlensing analysis includes the creation of many random realizations of the star fields near each image and the generation of magnification maps.

Microlensing Light-Curves

z = 0.66 RXJ 1131-1231





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Dissecting an Accretion Disk with Microlensing

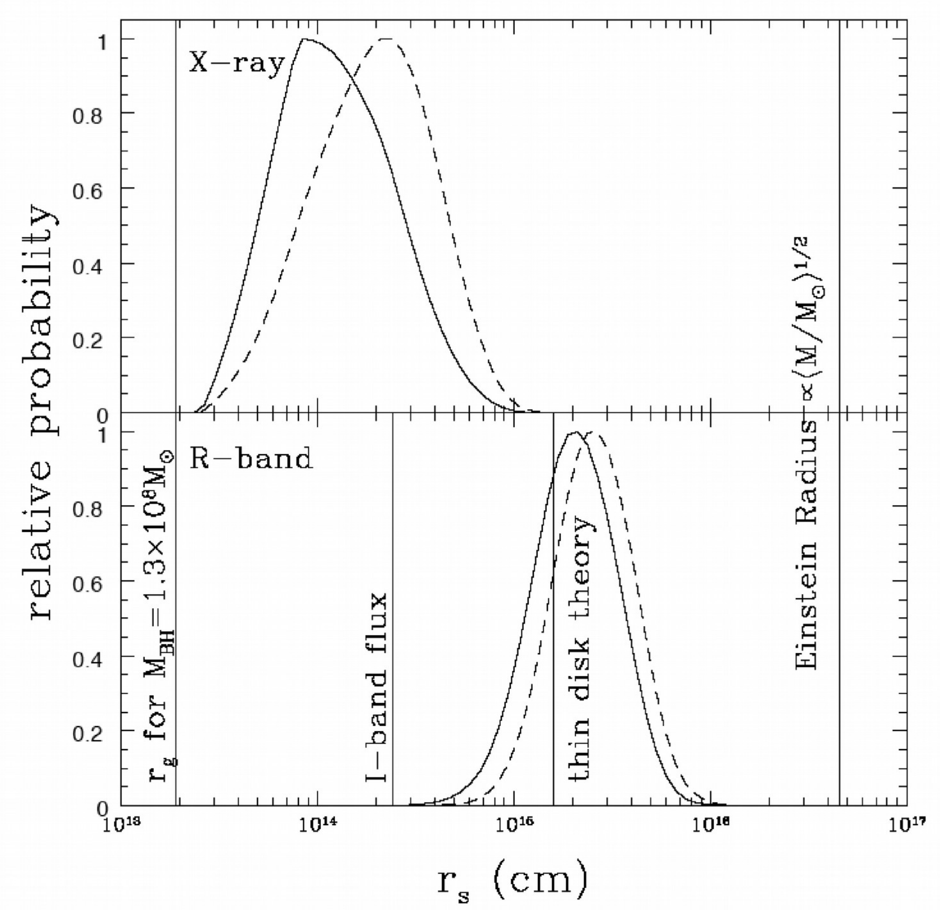
RXJ1131-1231

- Microlensing measurements of the sizes of the X-ray and Optical (400nm rest) emission regions of the z = 0.66 quasar RXJ1131-1231 indicate:

- X-ray corona size 10-20 r_g

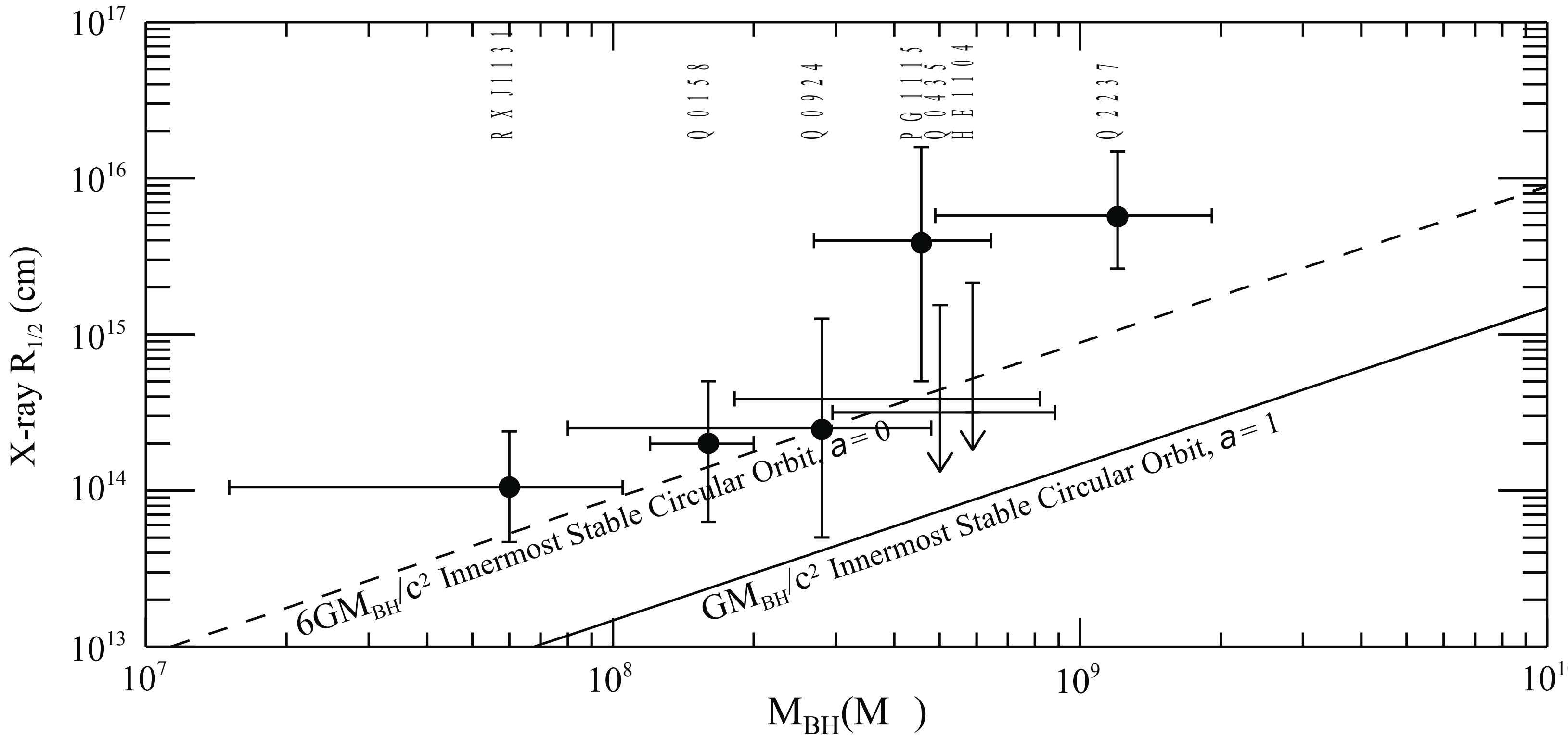
- Optical accretion disk size ~ 100 r_g

$M_{BH} \sim 6 \times 10^7 M_\odot$ (Hβ)



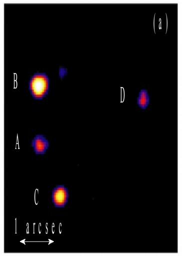
Dai et al. 2010, ApJ

Constraints on Corona Size from Microlensing



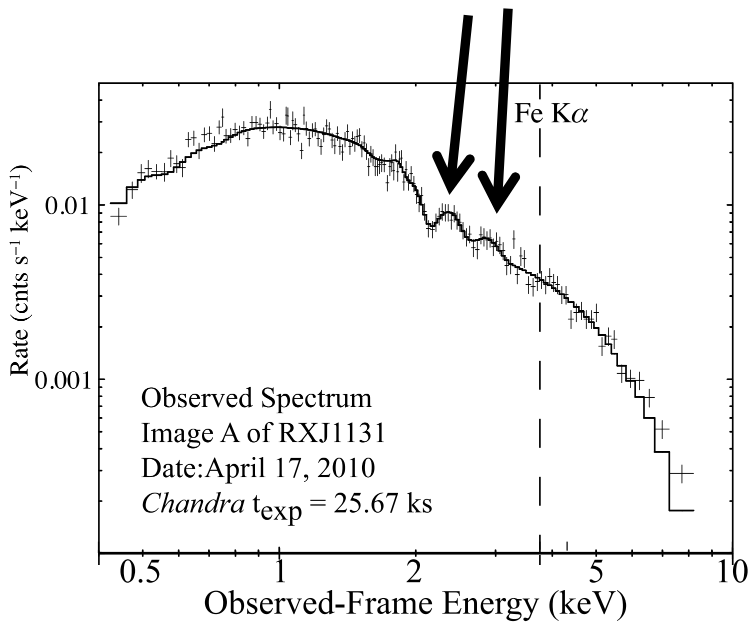
X-ray half-light radii of quasars as determined from our microlensing analysis versus their black hole masses.

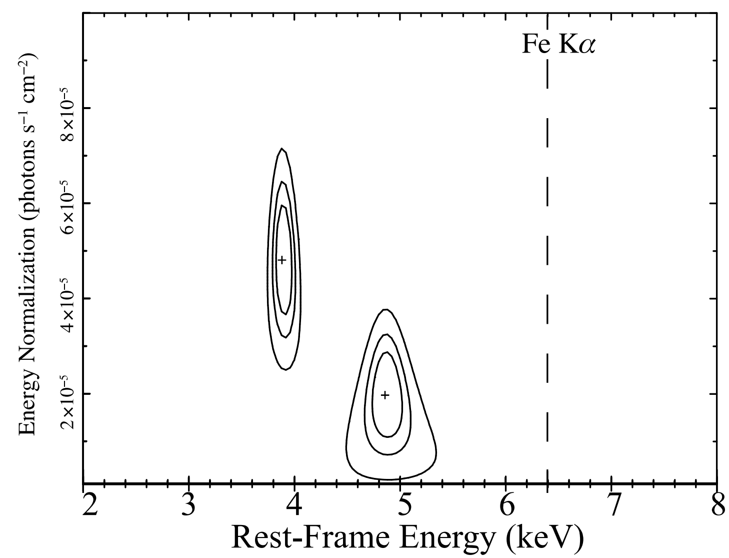
Evidence for Microlensed Fe lines in Quasar Spectra



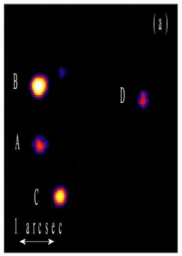
Shifted Fe Kα line in Spectrum of image A (4/17/2010)

"double"

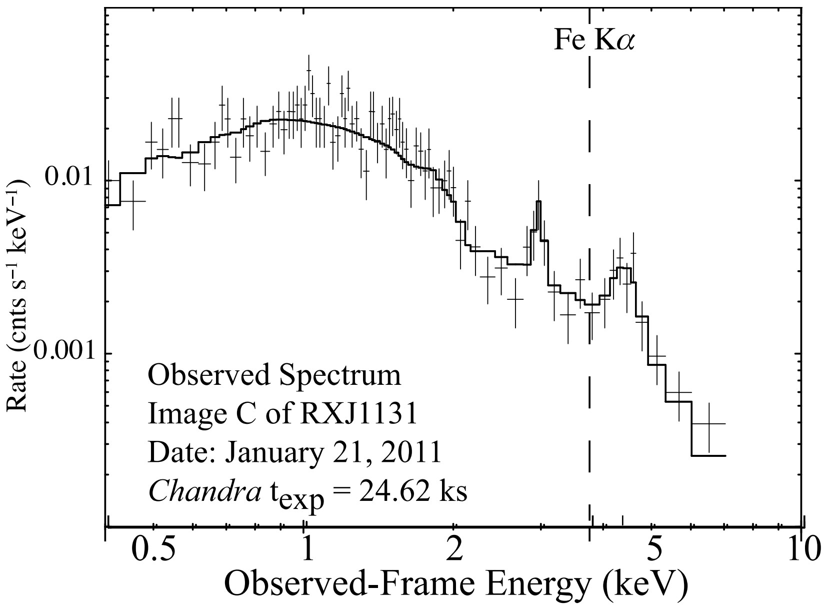


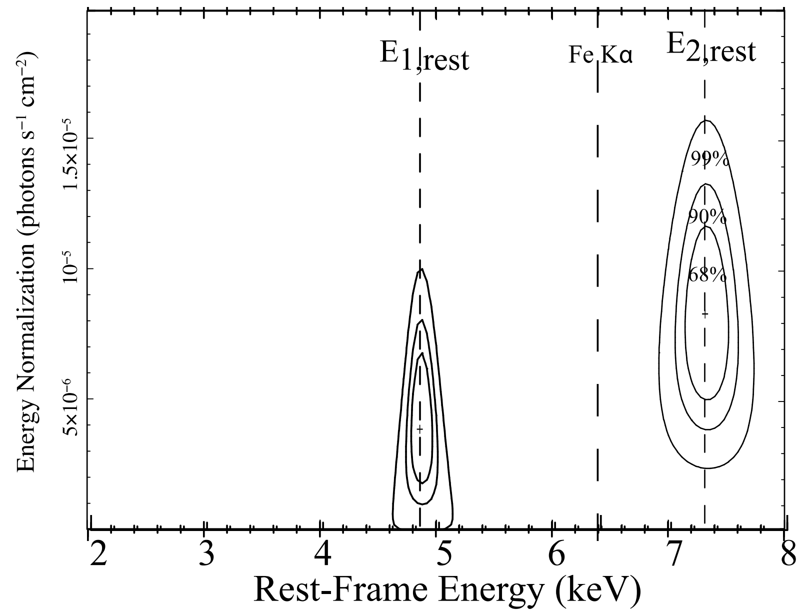


Evidence for Microlensed Fe lines in Quasar Spectra

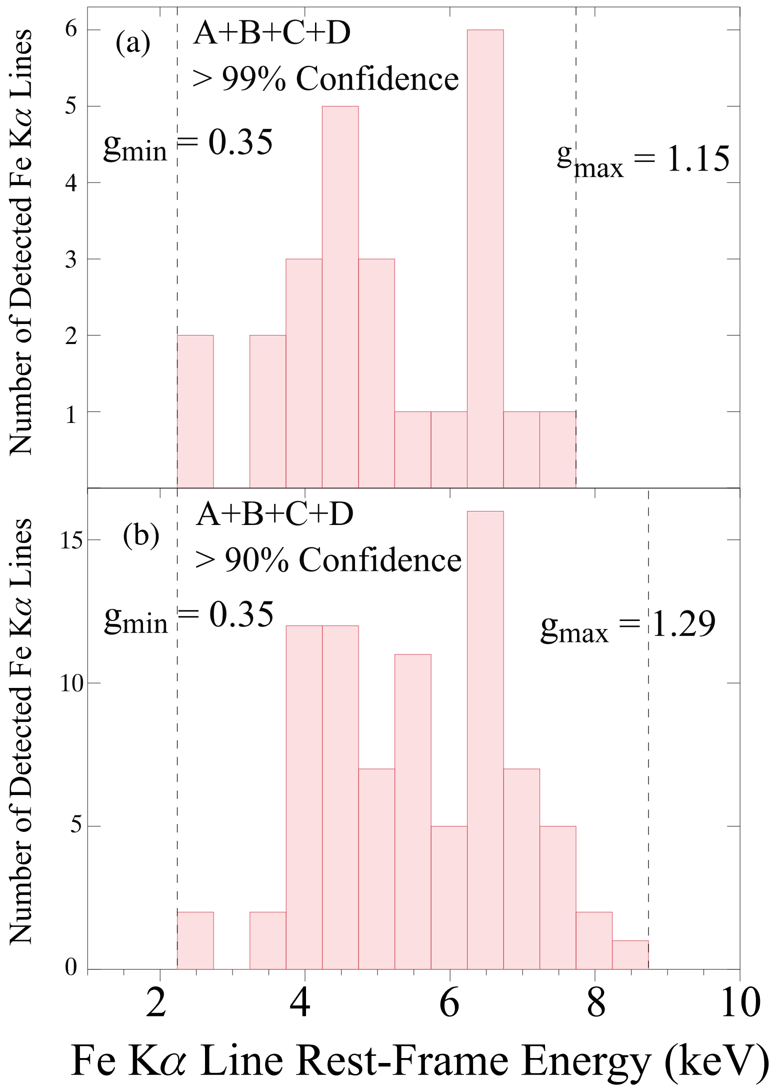


Shifted Fe Kα line in Spectrum of image C (1/21/2011)





g-Distribution of Fe Line Centroid Energies



Based on the analysis of 196 *Chandra* spectra:

49 epochs × 4 images
taken over a period of ~ 14 years

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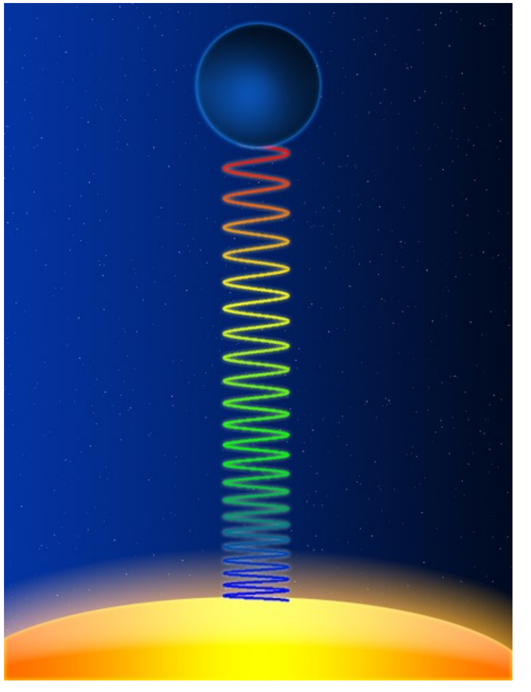
The Energy Shift of the Fe K line

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.

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



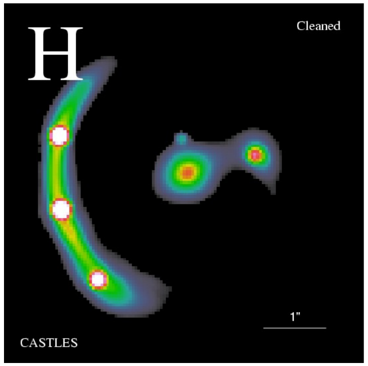
Where the Doppler shift is:

$\delta = \frac{\sqrt{1 - v_\phi^2}}{1 - v_\phi \cos\theta_c}$, where v_ϕ is the azimuthal velocity and θ_c is the angle between our line-of-sight and the direction of motion of the emitting plasma.

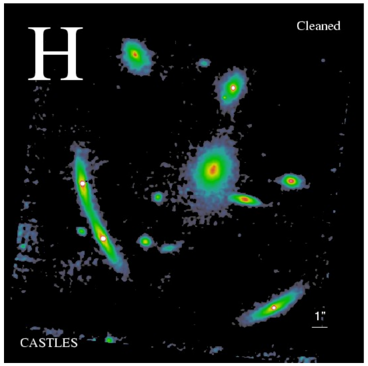
A, Σ, and Δ are defined as

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

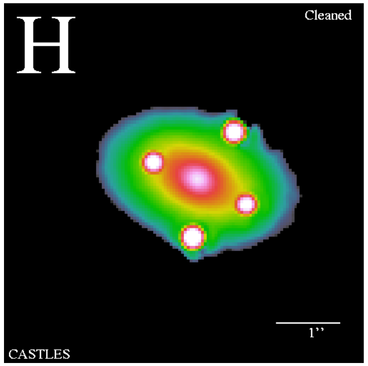
Constraints on the ISCO and Spin



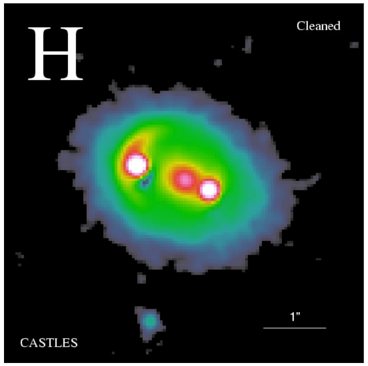
z=0.66 RXJ1131



z=1.73 SDSS1004



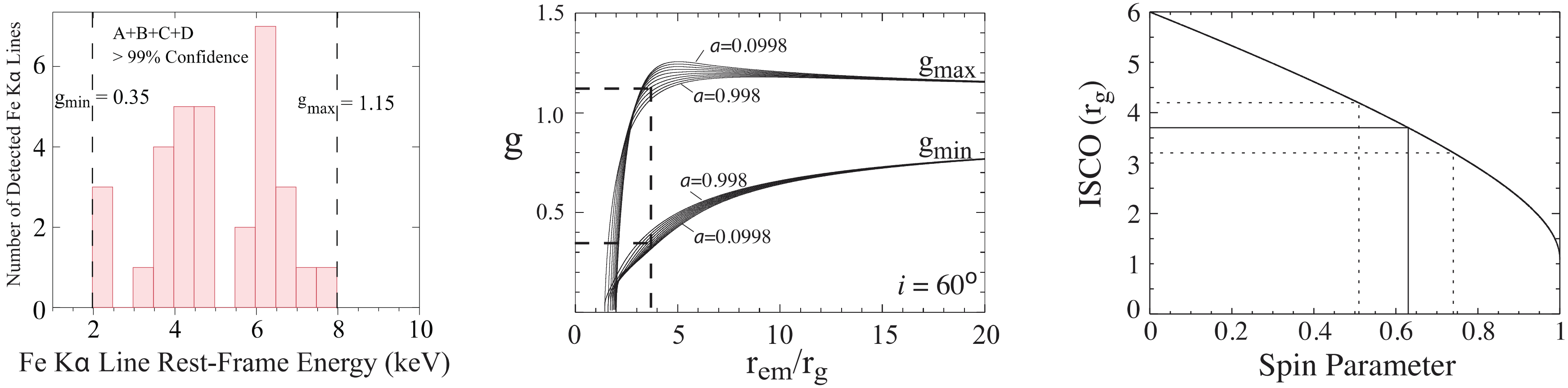
z=1.69 Q2237



z=1.29 QJ0158

Object	$\log(M_{\mathrm{BH}})$ $M_\odot$	$\log(R_{\mathrm{E}})$ cm	$\log(r_{\mathrm{g}})$ cm	R_E/v_e years	$10r_g/v_e$ months	v_e km/s	μ	$L_{\mathrm{Bol}}/L_{\mathrm{Edd}}$ (counts s^{-1})
RXJ1131	7.8	16.4	13.0	11.1	0.5	720	57	0.7
QJ0158	8.2	16.5	13.4	18.0	1.6	600	5	0.4
SDSS1004	9.3	16.4	14.5	9.4	14.5	785	70	0.01
Q2237	8.7	17.0	13.8	8.1	0.7	3890	16	0.04

Constraints on the ISCO and spin of RXJ1131



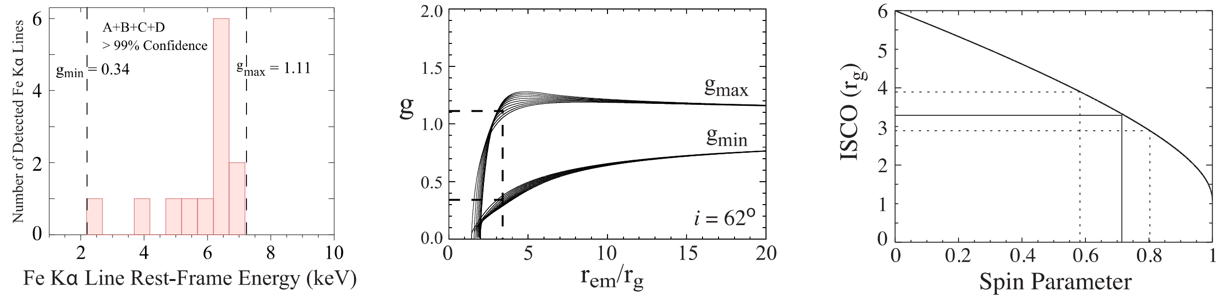
Left: Distribution of energy shifts of Fe K line

Middle: Observed and calculated extreme $g = E_{obs}/E_{rest}$ values as a function of distance from black hole center

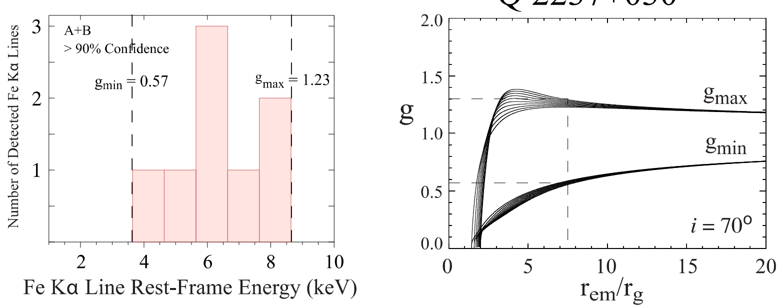
Right: Inferred spin parameter of RXJ1131: $a \sim 0.6 +/- 0.1$

*C*onstraints on the ISCO and Spin

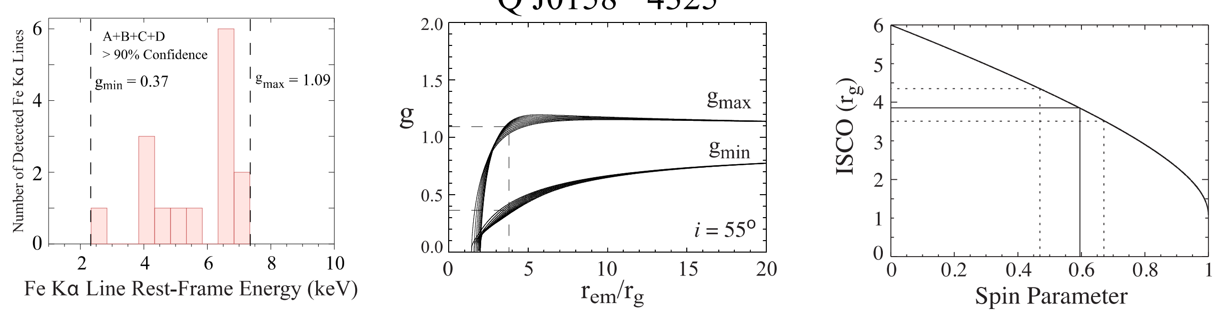
SDSS1004+4112



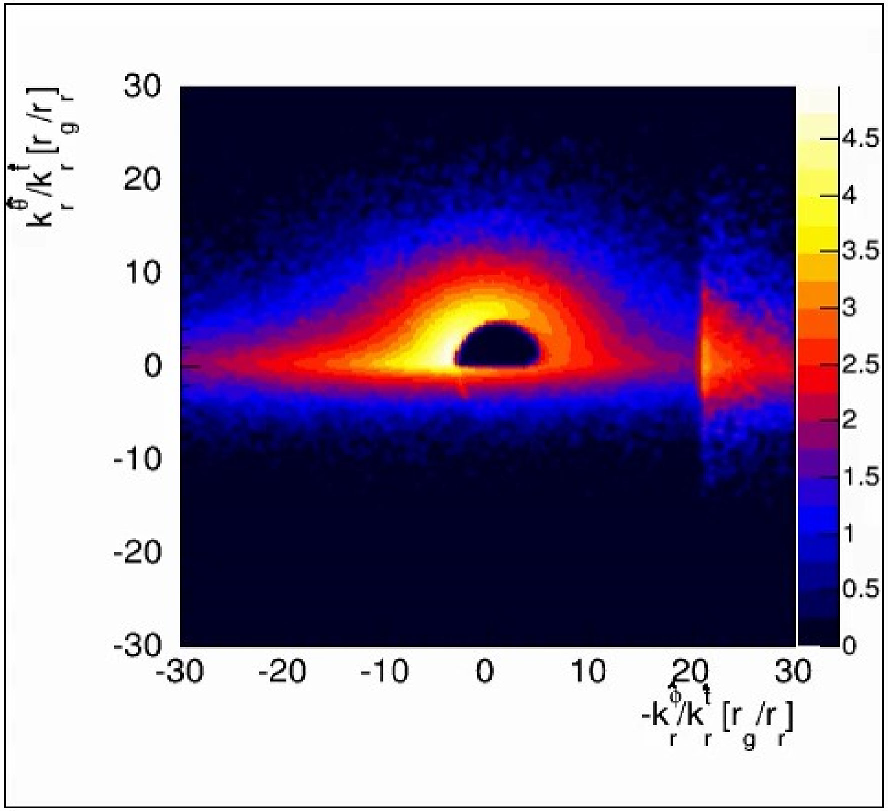
Q 2237+030

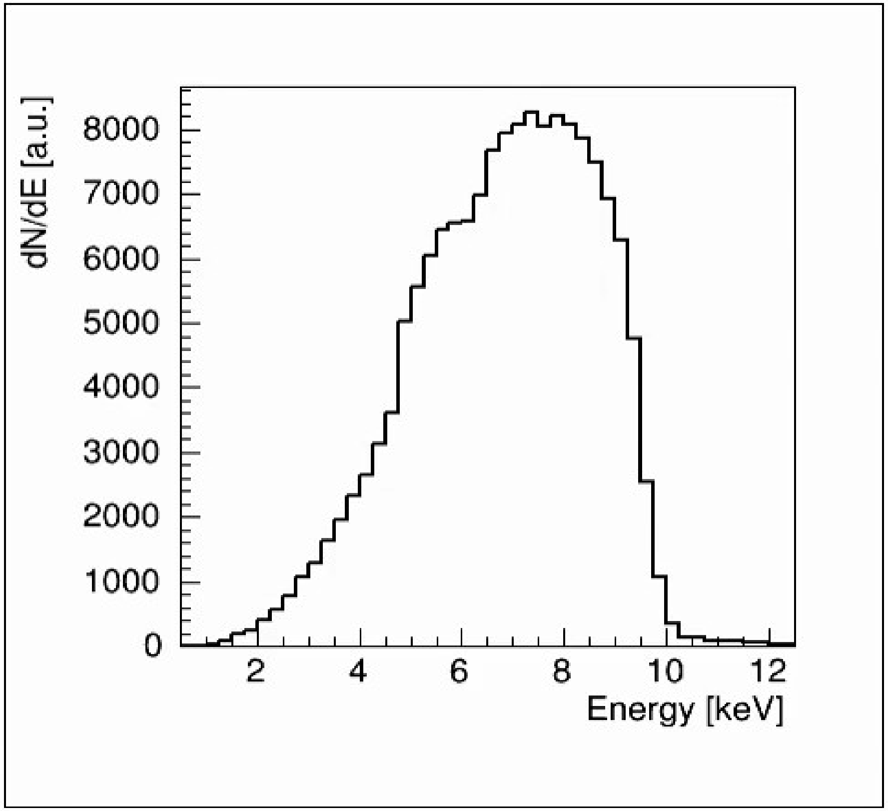


Q J0158− 4325



Simulations of X-ray Microlensing in Quasar RXJ1131





Chartas+ 2016, 2017; Krawczynski+ 2017

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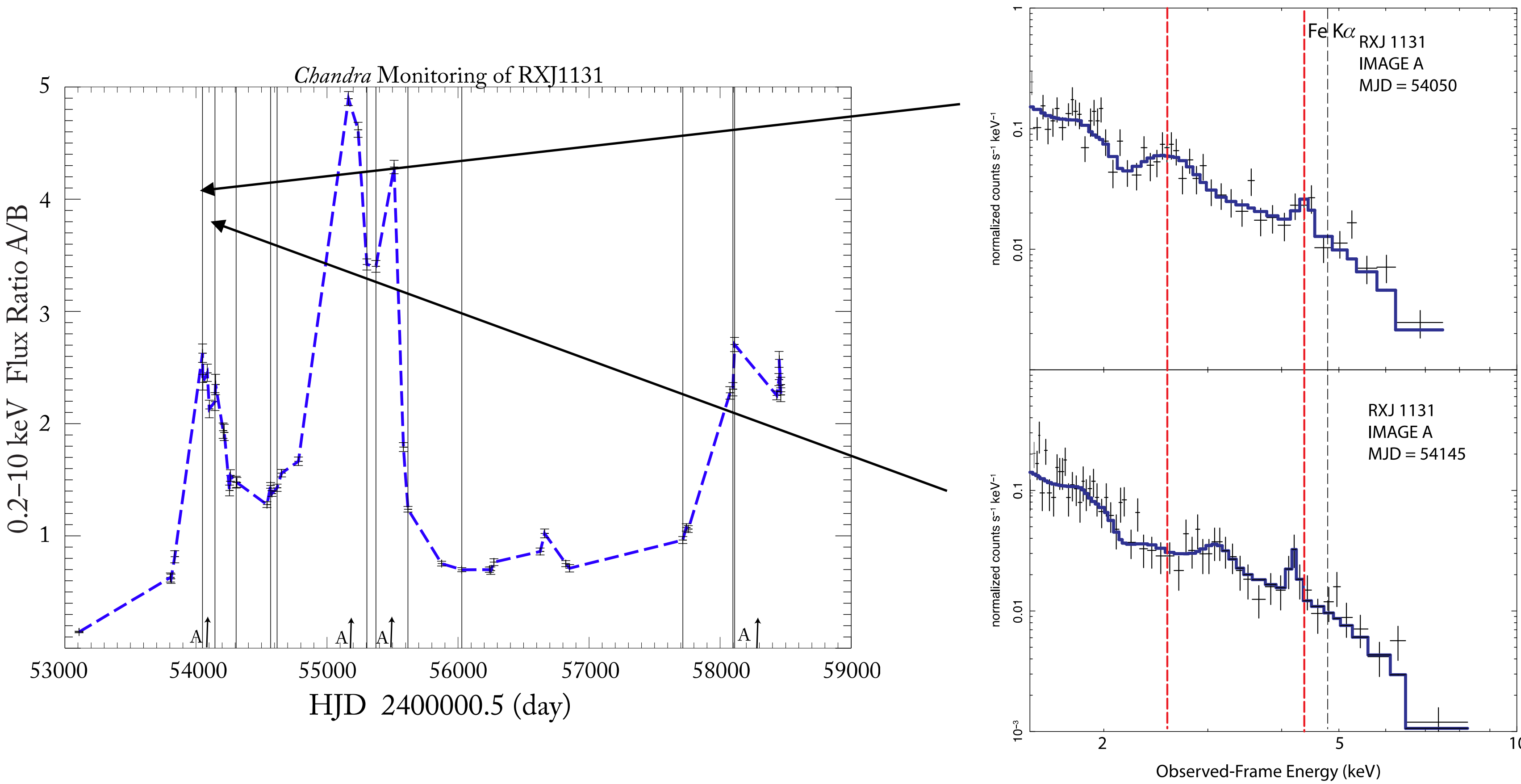
Observations of single caustic crossing events

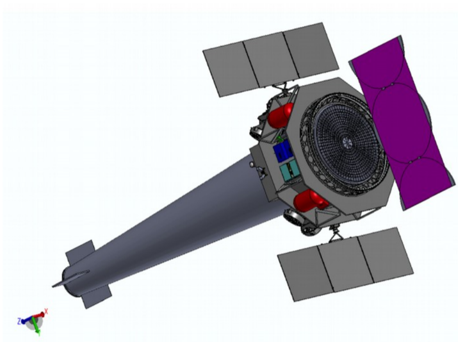


The detection of individual caustic crossing events would be spectacular revealing the gradual change in the profile and energy of the Fe line as the caustic sweeps over the accretion disk and corona.

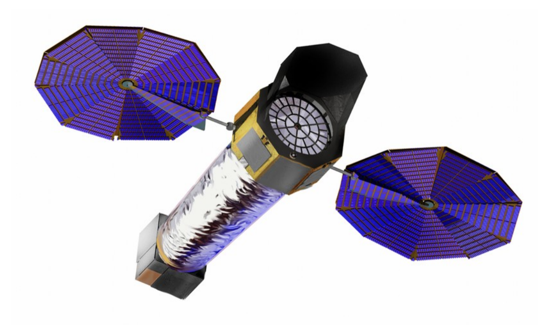
Future Prospects: Quasar Microlensing with *AXIS/Lynx*

1. Constrain the sizes of X-ray emitting regions of quasars ranging from the hot corona and inner accretion flow to the molecular and dusty torus

2. Constrain the evolution of the SMBH spins of quasars

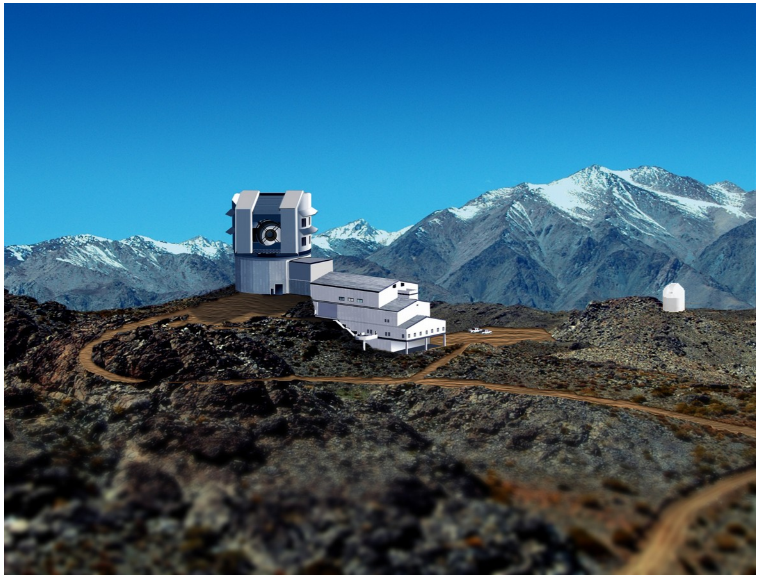


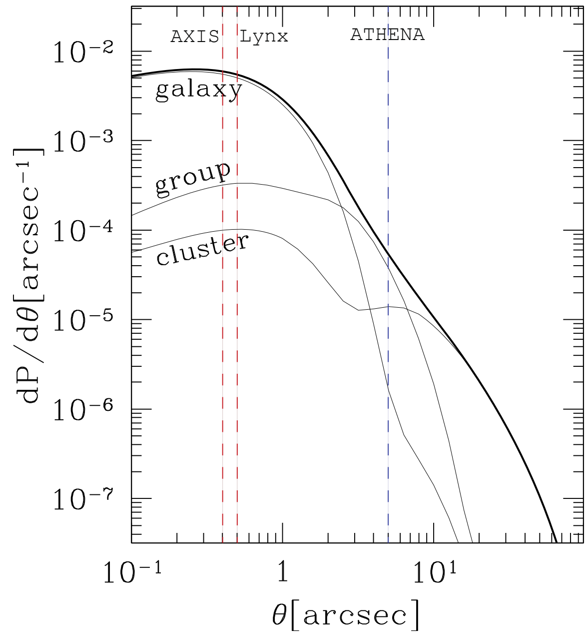
AXIS: A Probe-class mission that surpasses *Chandra* in angular resolution by a factor of ~2 and sensitivity by an order of magnitude. This mission can be launched in the late 2020s.



Lynx: is the high-energy flagship mission concept funded for study by NASA for consideration in the 2020 Astrophysics Decadal Survey. Angular resolution ~ 0.5 arcsec (HPD) and effective area of 2 m^2 (at 1keV)

Synergy with LSST





The Large Synoptic Survey Telescope (LSST) will discover > 4000 gravitationally lensed quasars that can be resolved by AXIS and Lynx.

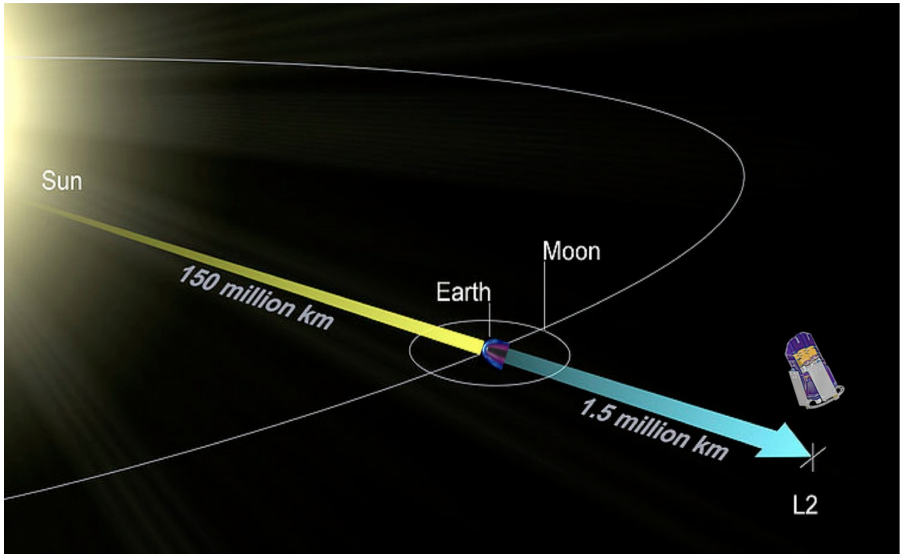
The planned observing window of AXIS (~2029-2034) will overlap with the multiband photometric optical surveys of LSST(~2023-2033), GAIA and EUCLID.

LSST will provide the triggers for microlensing events. These triggers can be used to begin dense *AXIS* monitoring of single caustic crossing events.

Synergy with *eROSITA*

- The X-ray fluxes of the newly discovered by **LSST** lensed quasars will have to be obtained through X-ray observations to determine which lensed systems are suitable for X-ray monitoring of caustic crossings.

- **eROSITA** will perform an all sky survey and will provide the X-ray fluxes of the lensed quasars that are bright enough to be monitored for microlensing events.



Conclusions

- Microlensing analysis of quasars constrains the size of their hot coronae to < 10 rg.

- Redshifted and blueshifted **Fe lines** with equivalent widths between 500-3000 eV are detected in lensed quasars. We interpret these energy shifts as the **result of microlensing of accretion disk** emission.

- For RXJ1131 we find $\boldsymbol{i \sim 60°}$, $\mathbf{r_{ISCO} \sim 3.7r_g}$ and $\boldsymbol{a = 0.6 +/- 0.1}$
- For SDSS1004 we find $\boldsymbol{i \sim 62°}$, $\mathbf{r_{ISCO} \sim 3.3r_g}$ and $\boldsymbol{a = 0.7 +/- 0.1}$
- For Q2237 we find $\mathbf{r_{ISCO} \lesssim 7.5r_g}$
- For QJ0158 we find $\boldsymbol{i \sim 55°}$, $\mathbf{r_{ISCO} \sim 3.7r_g}$ and $\boldsymbol{a = 0.6 +/- 0.1}$

- Several spectra show two shifted Fe lines (**doubles**). Our numerical simulations roughly reproduce the observable results.

- LSST will discover > 4000 lensed quasars bringing in a new era of X-ray lensing studies of quasars and galaxies