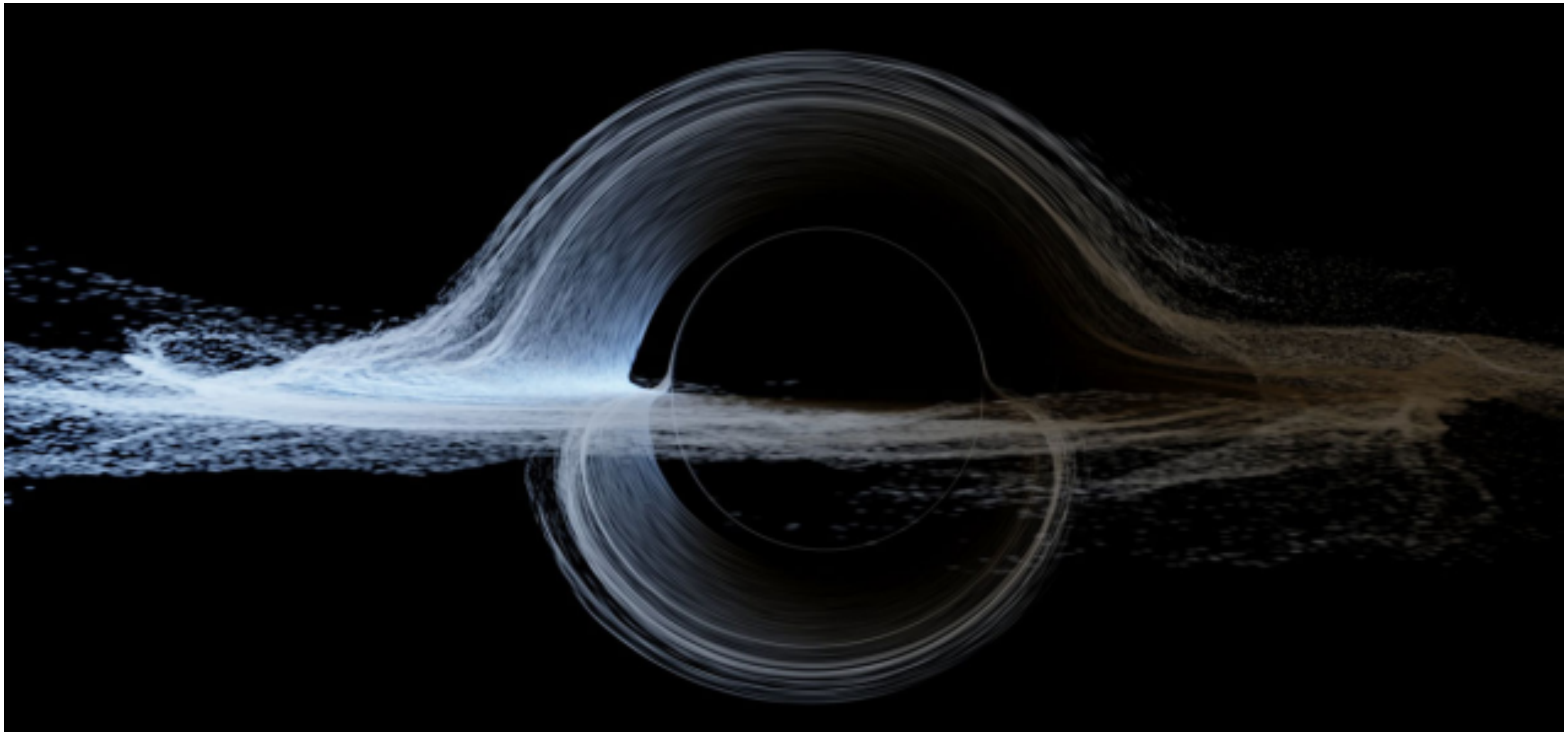
Using Microlensing to Probe Strong Gravity Near Supermassive Black Holes



Interstellar: Kip Thorne and Double Negative visual-effects team

Presented by: George Chartas

The X-ray Universe 2017

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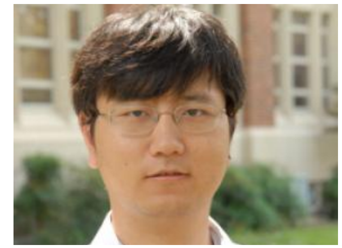

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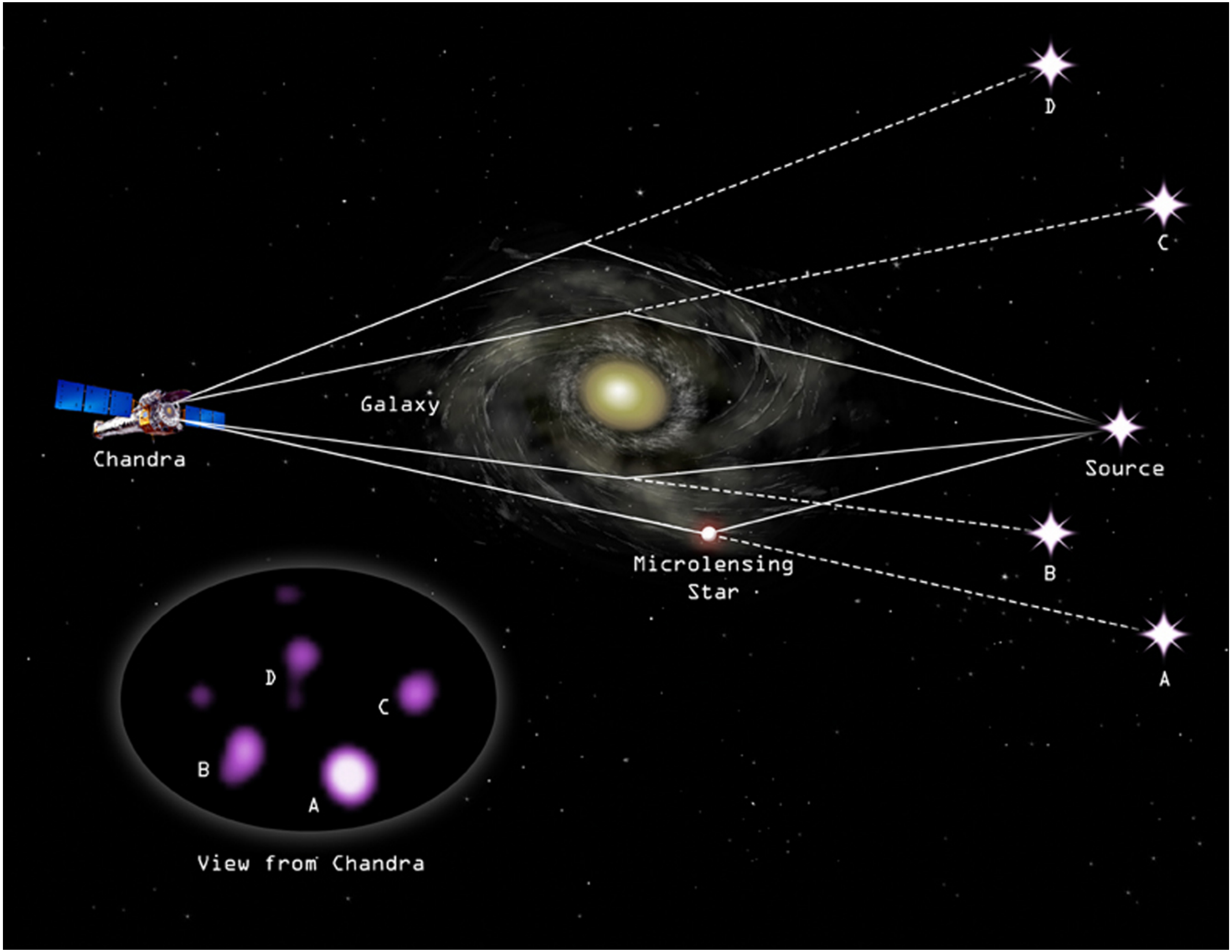
Outline

- Microlensing used for indirect mapping of disk and corona
- Monitoring of Lensed Quasars
- Constraints on inclination, ISCO, and spin
- Conclusions


D
C
Galaxy
Chandra
Source
B
Microlensing
Star
A
D
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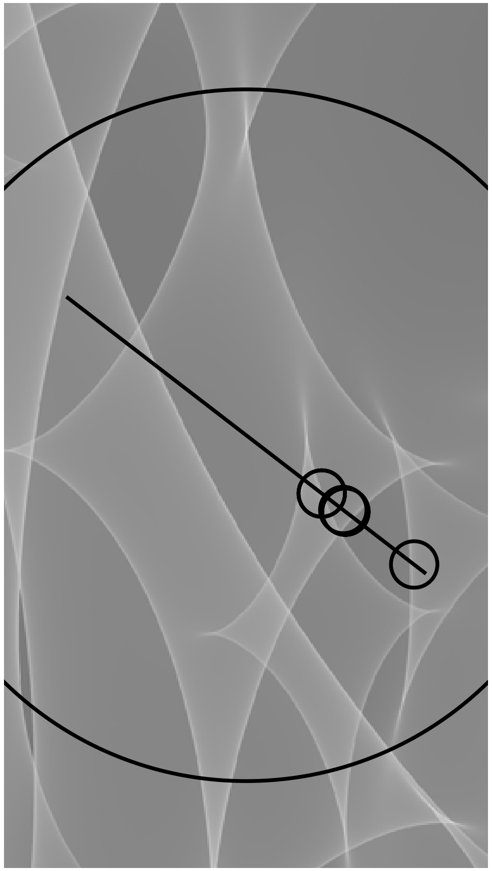
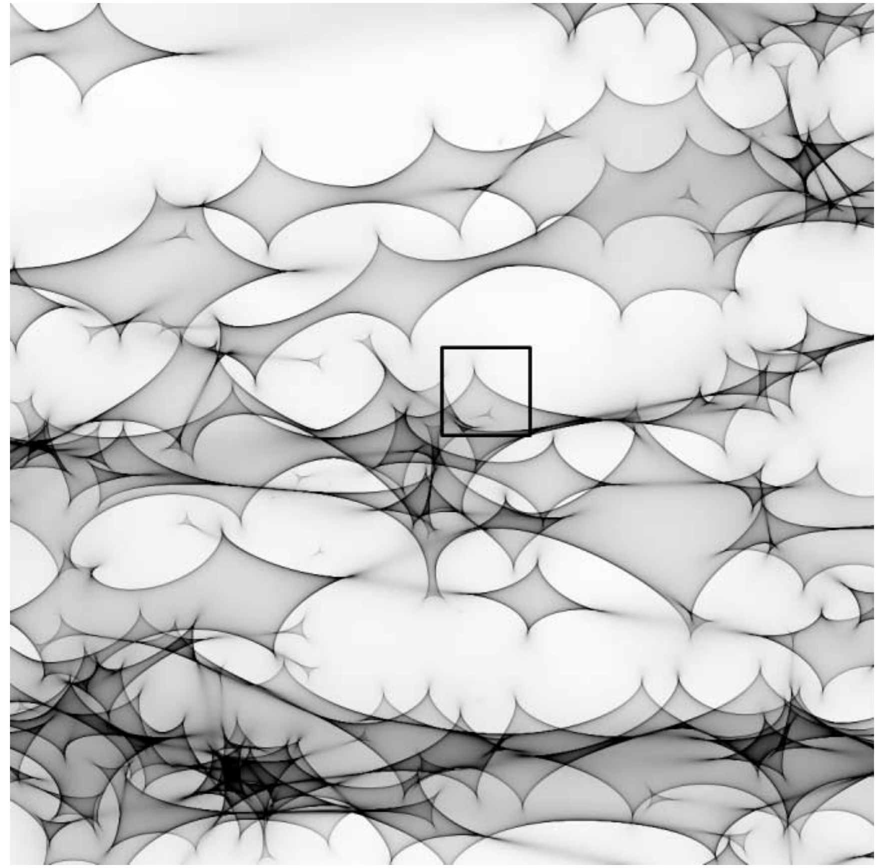
B
A
View from Chandra

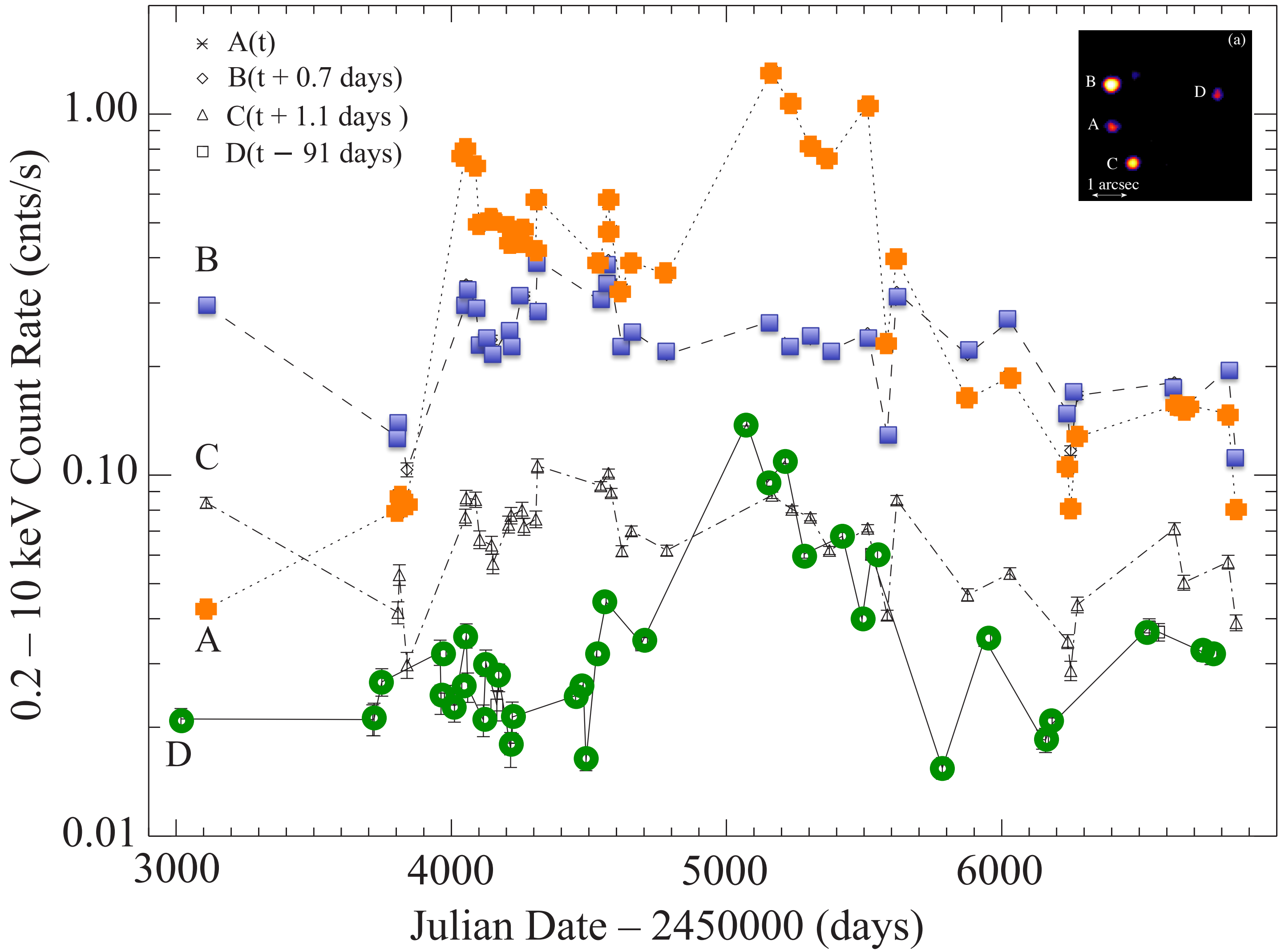


Simulated magnification map of image B of RXJ 1131 (Dai et al. 2010)



Microlensing map of QSO 2237+0305A image

Microlensing detected in 0.2 – 10 keV light-curves of RXJ1131



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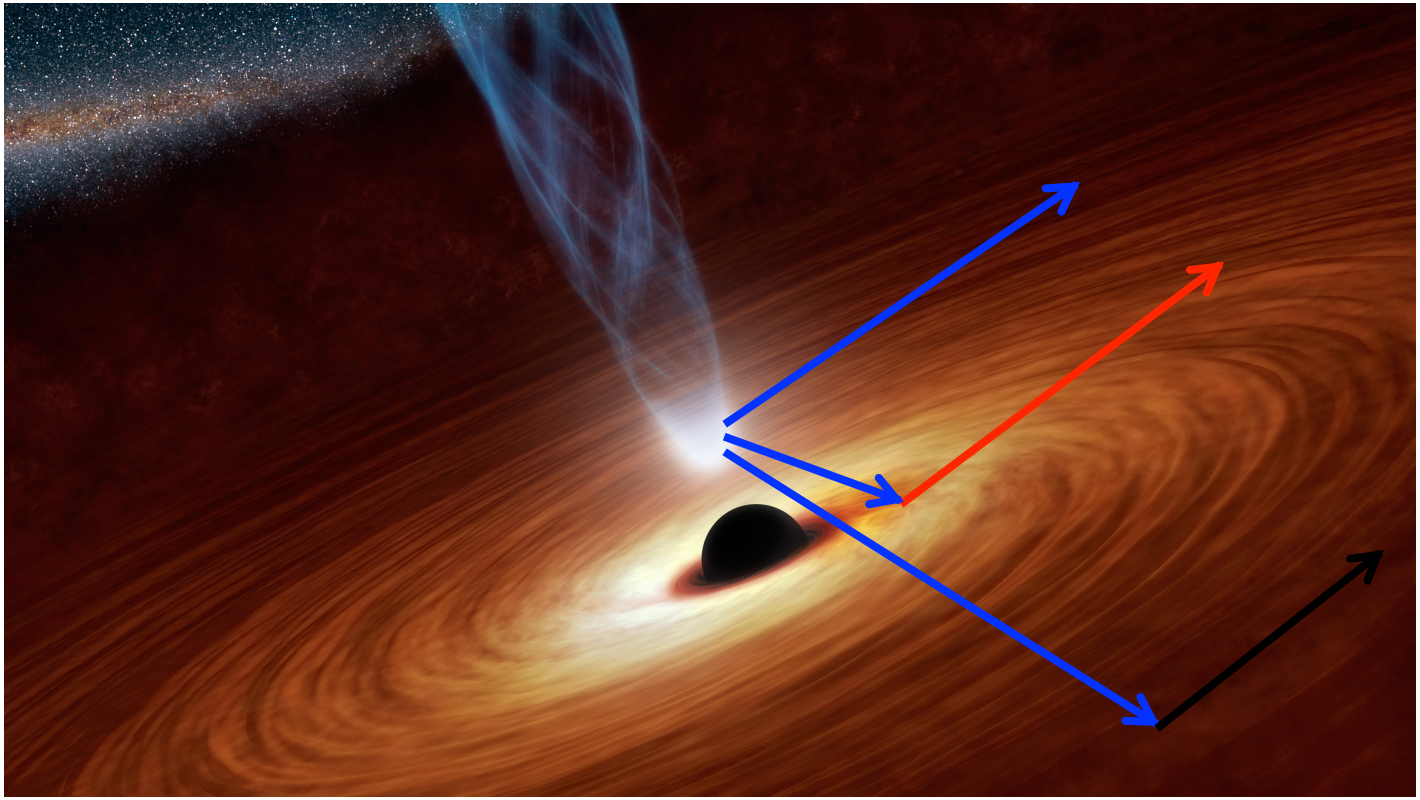
Fiducial Model



X-ray Power-Law from compact corona

Relativistically Blurred Reflection (line + continuum)

Distant Reflection (line + continuum)

Geometrically thin, optically thick accretion disk emitting primarily in UV/Optical

Dissecting an Accretion Disk with Microlensing

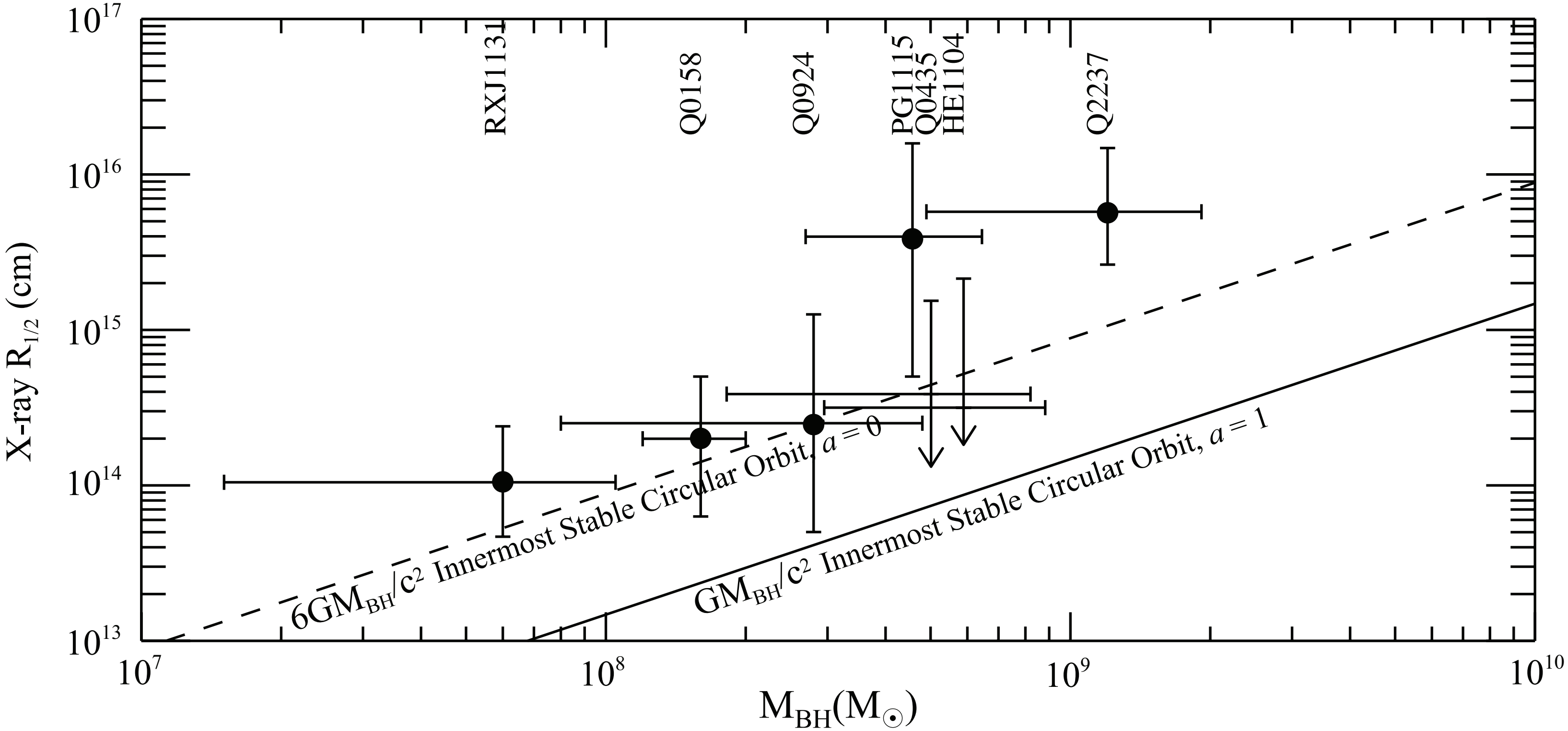
- We are performing multiwavelength monitoring of several quasars :

RX J1131-1231 ($z_s = 0.658$, $z_l = 0.295$)
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 are performed with *Chandra*
- *Optical* (*B*, *R* and *I* band) observations are made with the SMARTS Consortium 1.3m telescope in Chile.

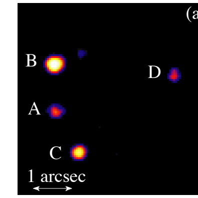
Constraints on Corona Size from Microlensing



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

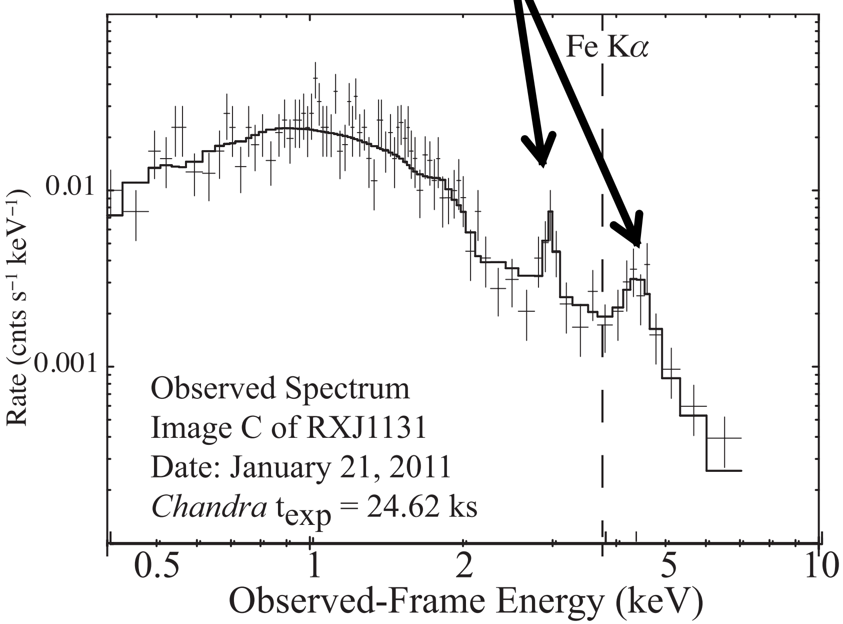
Chartas+2016

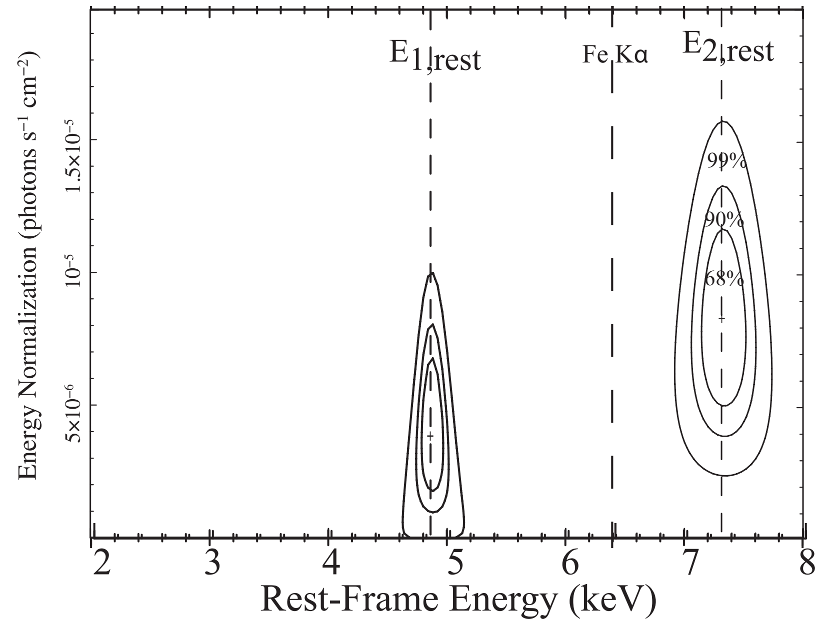
Evidence for Microlensing in all Images of RXJ1131



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

“Double”

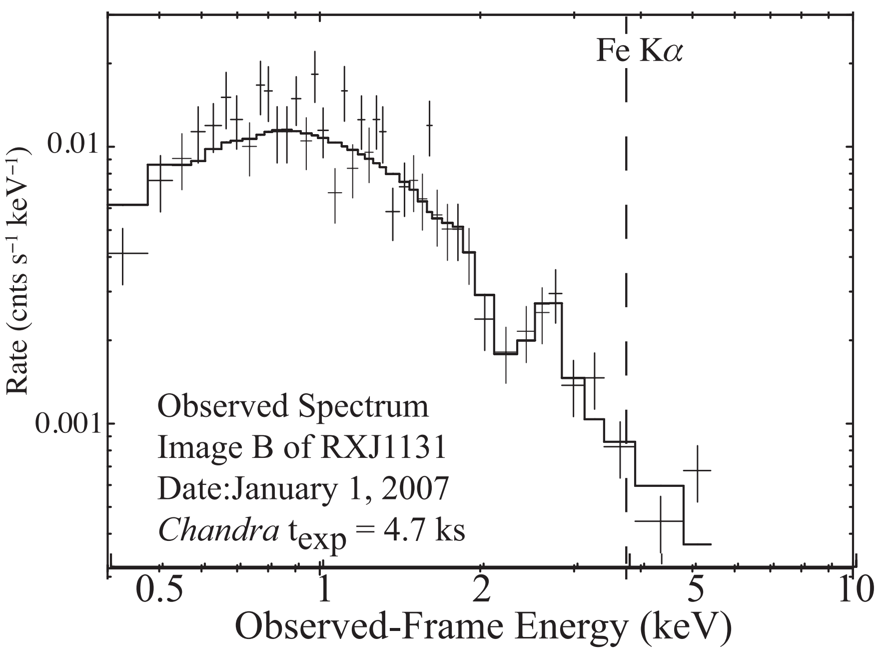


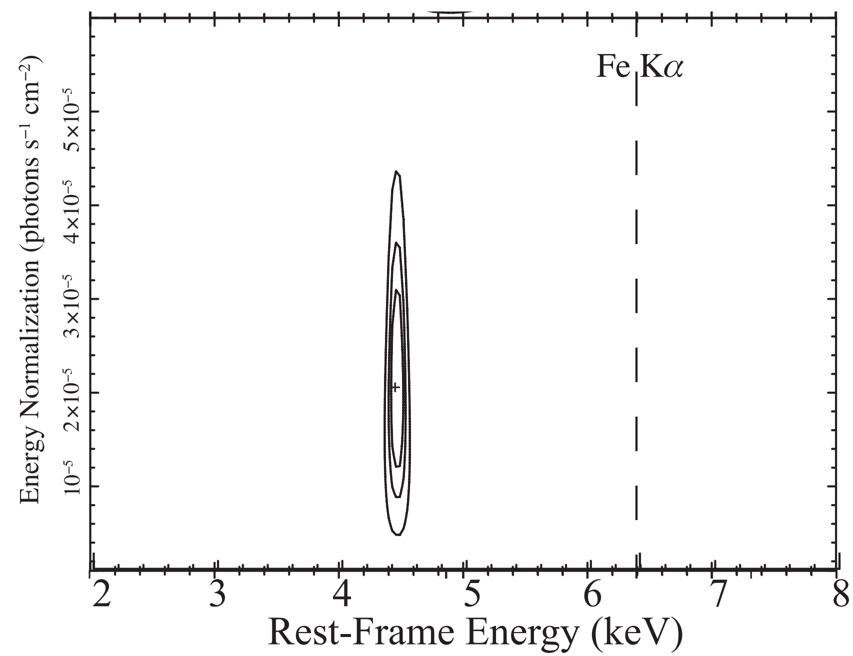


- 4 images × 38 pointings = 152 spectra
- 78 lines (>90%CL), 21 lines (>99%CL)

Evidence for Microlensing in all Images of RXJ1131

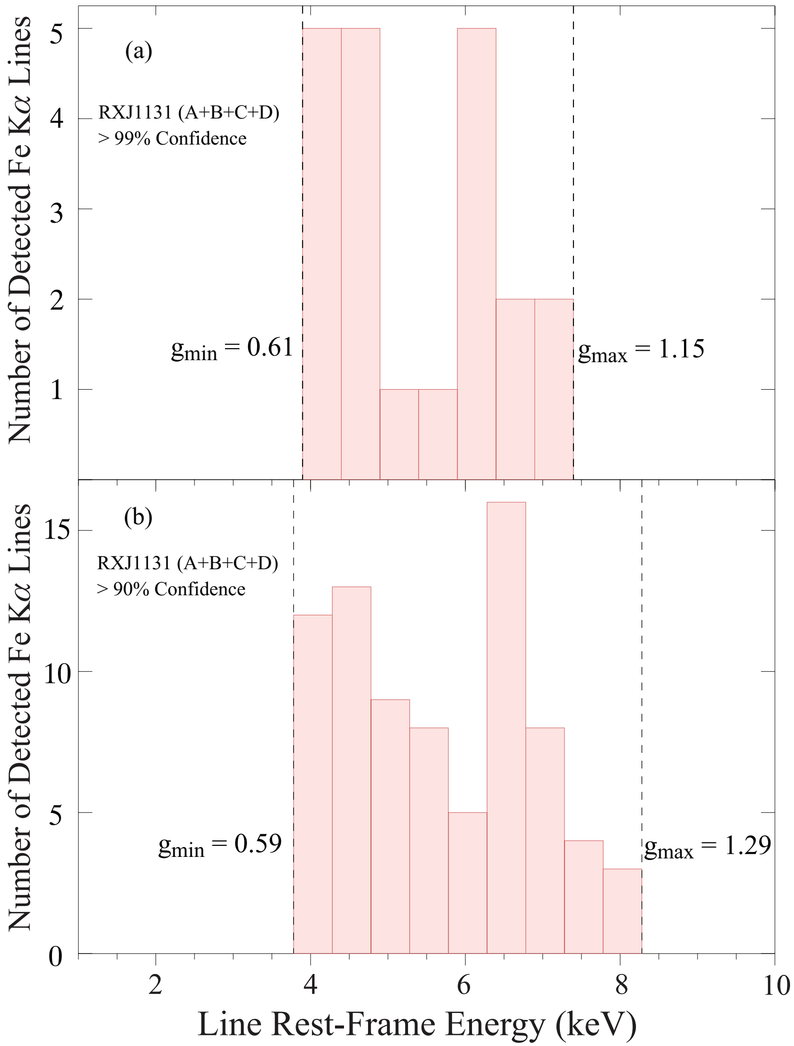
Shifted Fe Kα line in Spectrum of image B (1/1/2007)





Significant spectral variability, including the centroid and equivalent width of the Fe Kα line

g-Distribution of Line Centroids of RXJ1131

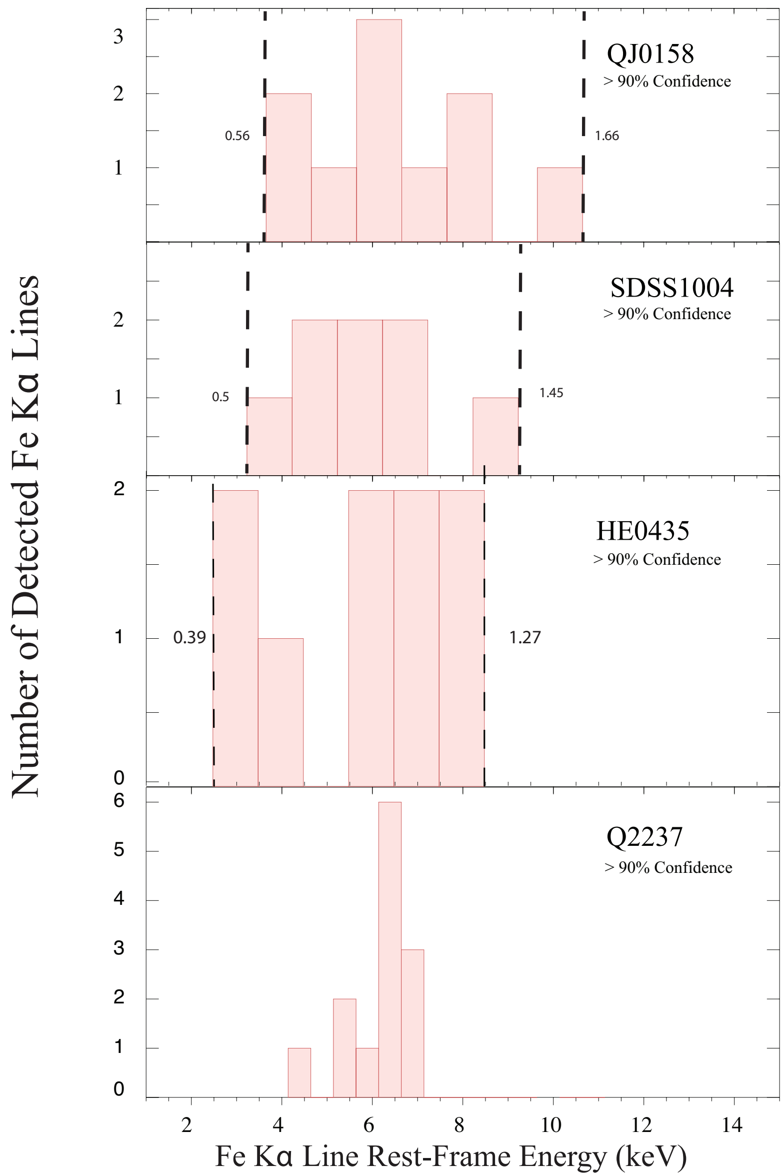


Chartas et al. 2017

Red/blueshift: 0.61-1.15 (99% CL)

Red/blueshift: 0.59-1.29 (90% CL)

g-Distribution of Line Centroids



QJ0158-4325 ($z_s = 1.29$, $z_l = 0.317$)

SDSS1004+4122 ($z_s = 1.734$, $z_l = 0.68$)

HE 0435-1223 ($z_s = 1.689$, $z_l = 0.46$)

Extremal shifts of the Fe Kα line energy in HE 0435 imply

- $3r_g < r_{ISCO} < 4r_g$
- spin ~ 0.7

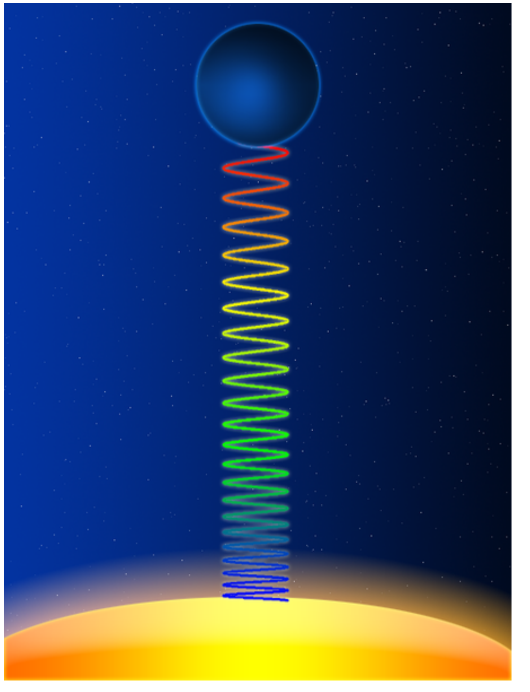
Q 2237+030 ($z_s = 1.60$, $z_l = 0.04$)

g_{max} ~ 7 keV implies face on geometry

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.

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



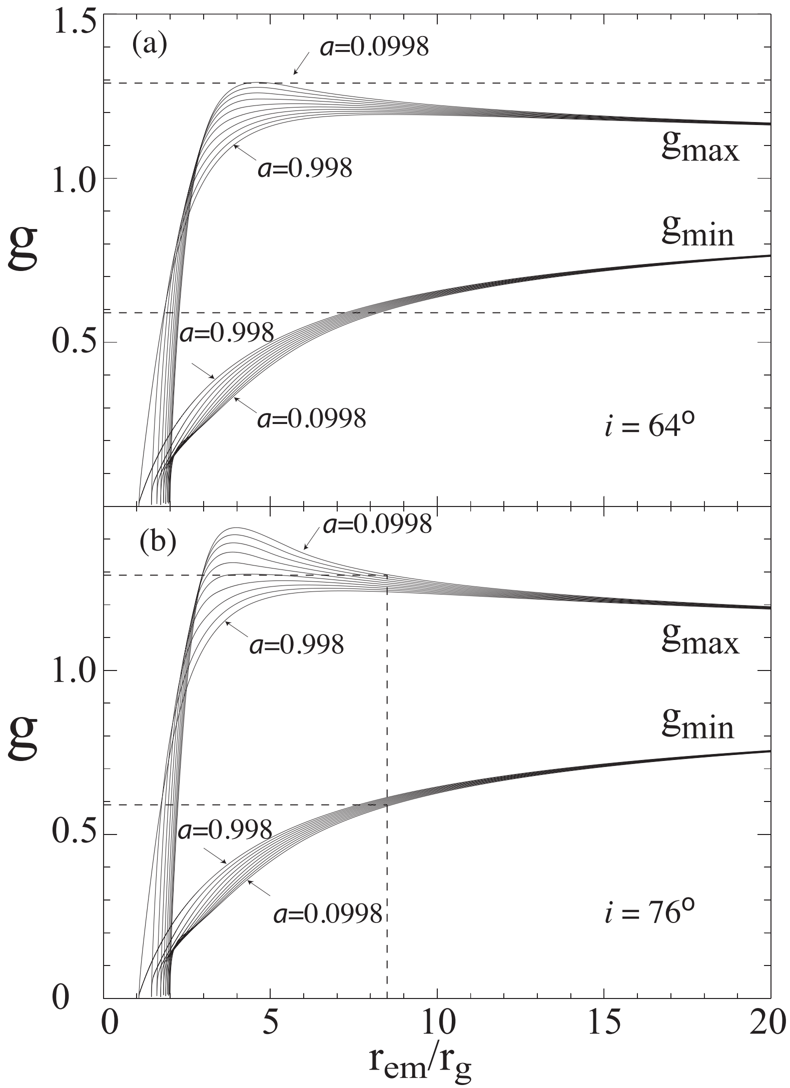
Where the Doppler shift is:

$\delta = \dfrac{\sqrt{1 - v_\phi^2}}{1 - v_\phi \cos\theta_c}$, 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

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

g versus radius for RXJ1131



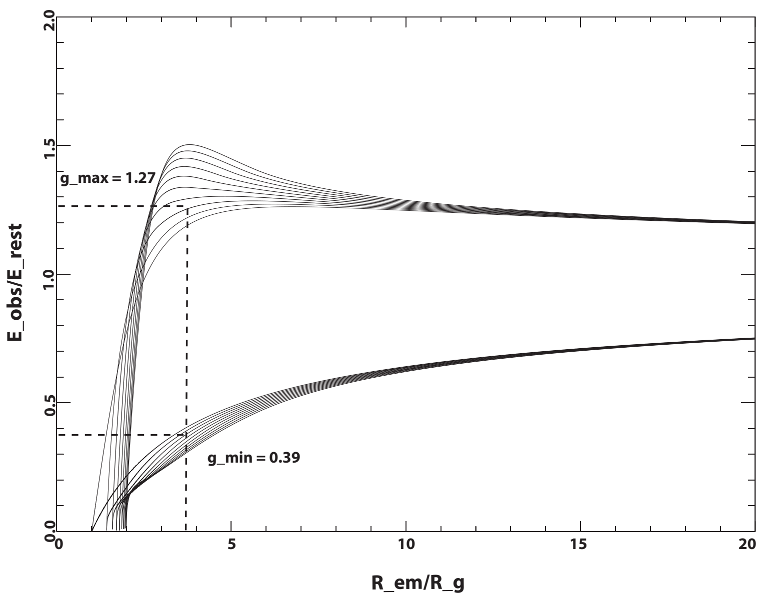
$g_{max} = 1.29$ ➔ $i > 64°$

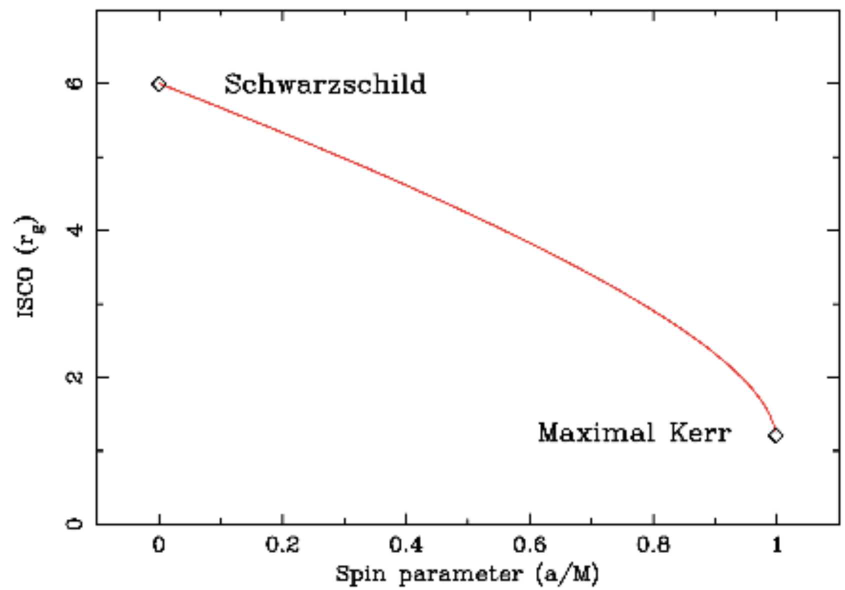
$g_{max} = 1.29$ ➔ $i > 76°$

$g_{min} = 0.59$ $r_{ISCO} < 8r_g$

Assume g_{min} and g_{max} occur at same radius

g versus radius for HE0435





Extremal shifts of the Fe Kα line energy in HE 0435 imply $3r_g < r_{ISCO} < 4r_g$

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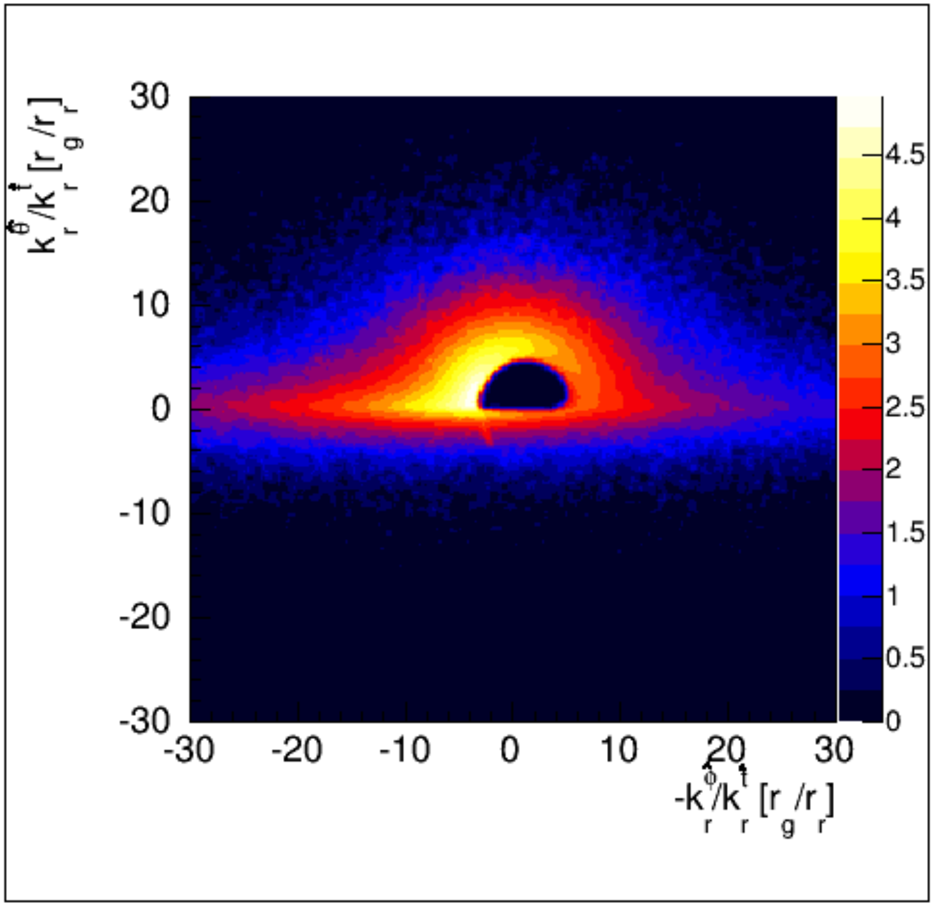
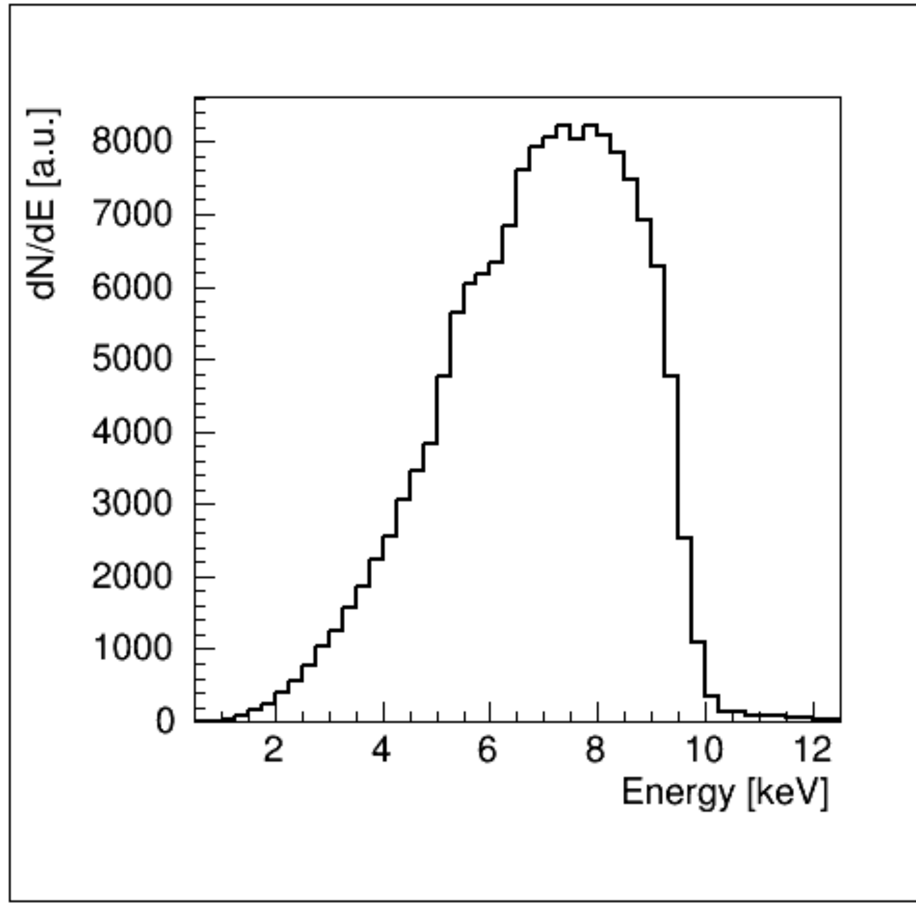
Numerical Simulations of Microlensing Events





Chartas+ 2016, 2017; Krawczynski+ 2017

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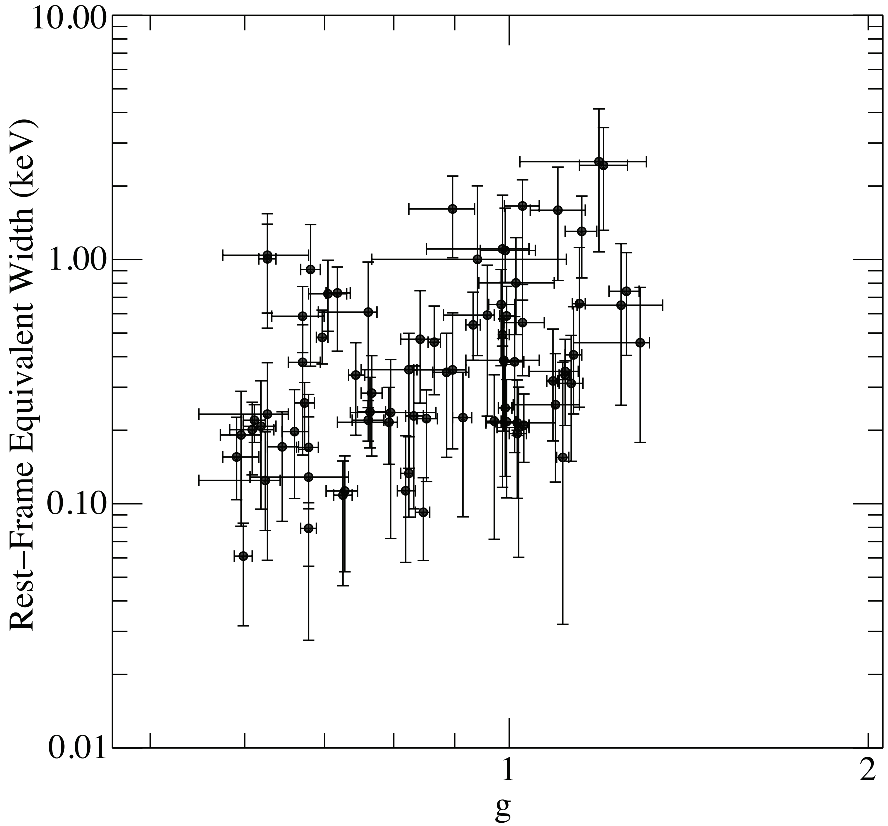
g **versus** Equivalent Width of shifted Fe Kα Line



Correlation of *g* vs. EW
Kendall's $\tau = 0.3$, P > 99.9% CL

One possible explanation of this correlation is that blueshifted line emission is Doppler boosted resulting in the observed EW of the blueshifted lines being larger than the redshifted lines.

Supports microlensing interpretation!

Conclusions

- Redshifted and blueshifted **Fe lines** with EWs between 500 − 3000 eV are detected in 5 lensed quasars. We interpret these energy shifts as the **result of microlensing of accretion disk** emission within ~ 20 r_g of the black hole.

- For RXJ1131 we constrain $\boldsymbol{i > 76°}$ and $\mathbf{r_{ISCO} < 8.5r_g}$. For HE 0435 we find $\mathbf{3r_g < r_{ISCO} < 4r_g}$

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

- Our simulations show that the distribution of the energy separations of doubles is strongly dependent on spin.

- The next step is to correct for selection bias, fit the results from the numerical simulations to the *Chandra* data and explore the dependence of the results on corona properties.