The Bardeen-Petterson effect

Unique evidence in Swift J2058+0516

Wenfei Yu
Shanghai Astronomical Observatory

E-mail: wenfei@shao.ac.cn

Content

- Bardeen-Petterson (B-P) effect
- Iron line as a probe of B-P effect
- Iron lines reverberation mapping to probe BH mass and spin
- Evidence of B-P effect in the TDE X-ray flare Swift J2058
  - complex line feature
- Discussions: probing dormant SMBH spins with the B-P effect

The Bardeen-Petterson (BP) effect

- A ***tilted*** accretion disk around a ***spinning*** black hole to warp into the equatorial plane of the spinning black hole.
- Combination of two effects: differential Lense-Thirring precession and internal viscosity of the accretion flow.

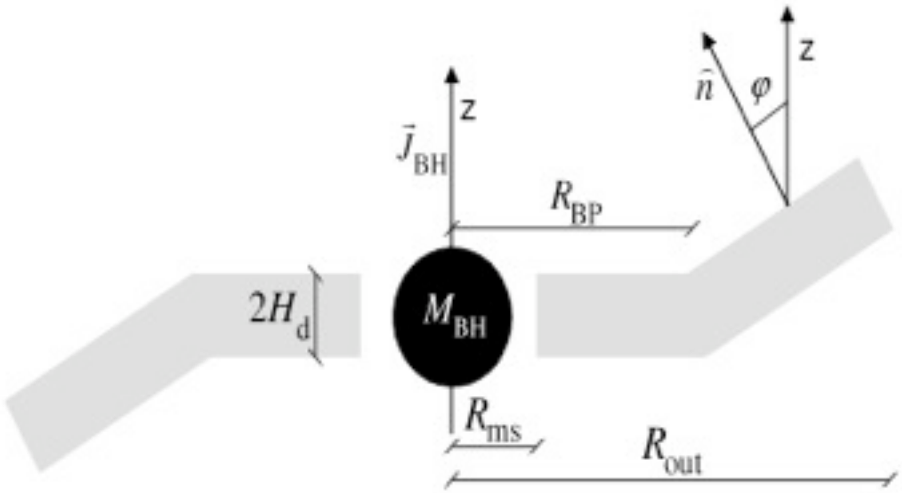
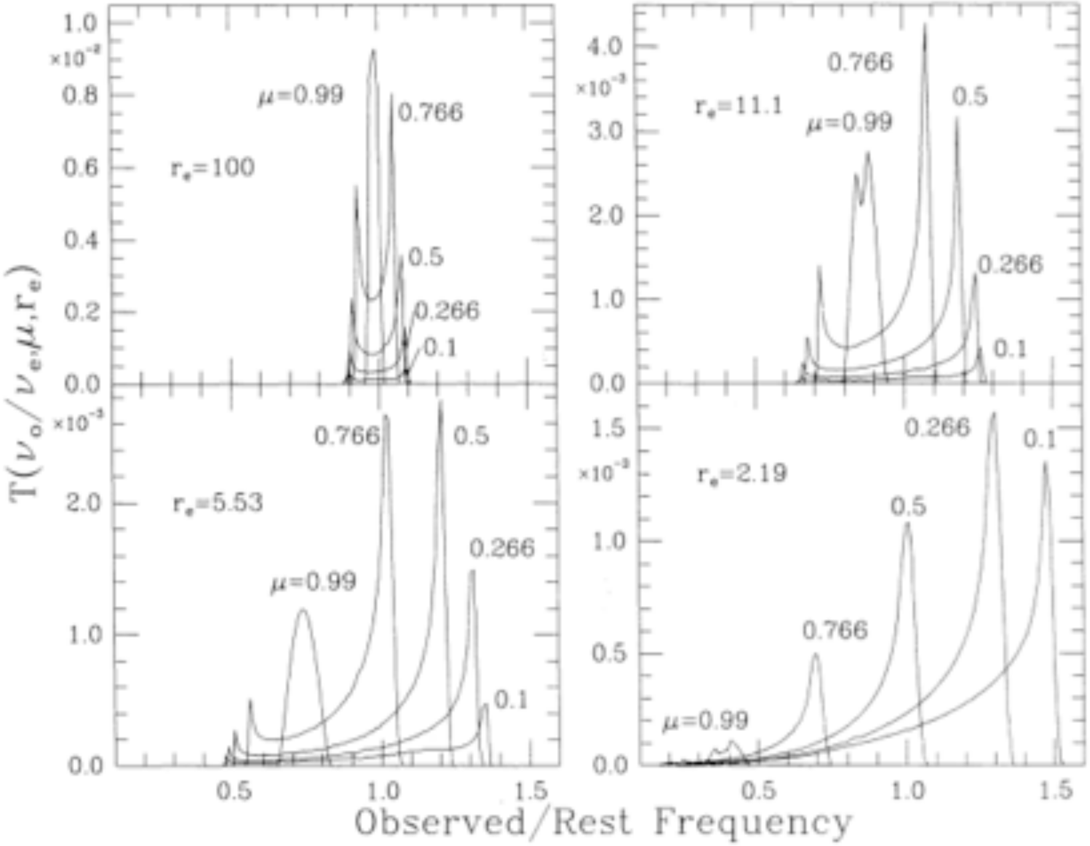


FIG. 1.—Schematic view of the Bardeen-Petterson effect. An accretion disk with inner and outer radius R_{ms} and R_{out}, respectively, having a semithickness H_d and misaligned initially by an angle φ in relation to the angular momentum of the black hole J_{BH} and mass M_{BH}, will be warped by the Bardeen-Petterson effect. The Bardeen-Petterson radius R_{BP} marks the transition between the aligned and misaligned disk in relation to the black hole's equator.

The BP radius is estimated as a few tens Rg

information of both the BH and the accretion flow

Disk line profile sensitive to disk inclination within 100 Rg



Relativistic line profiles around a spinning BH
(Laor 1991)

Sensitive probe of the innermost BP disks could be from disk lines.

Iron line as a probe of the Bardeen-Petterson disks

- inner disk deep in the potential, angular momentum aligned with the BH spin
- outer disk less affected by the BH spin
- broad, relativistic iron line turns into multiple peaks, depends on inclinations as well as the angle ϕ

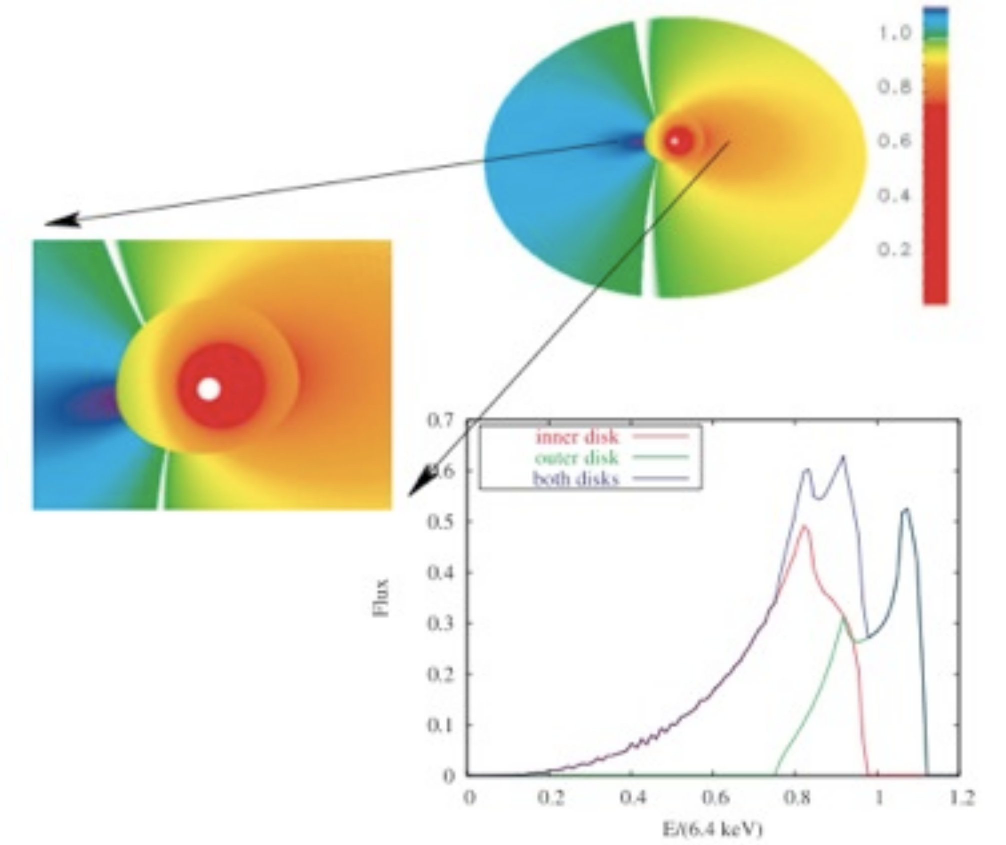


FIG. 1.—Example disk image of a two-component Bardeen-Petterson disk with $\beta = 30°$ and $r_{BP} = 15r_g$. The observer is located at $\phi_0 = 90°$ (line of sight perpendicular to the line of nodes) and is inclined 45° with respect to the outer disk and 15° with respect to the inner disk.

The line emission is primarily from two disk components

Fragile et al. 2005

Iron line profile of a Bardeen-Petterson disk

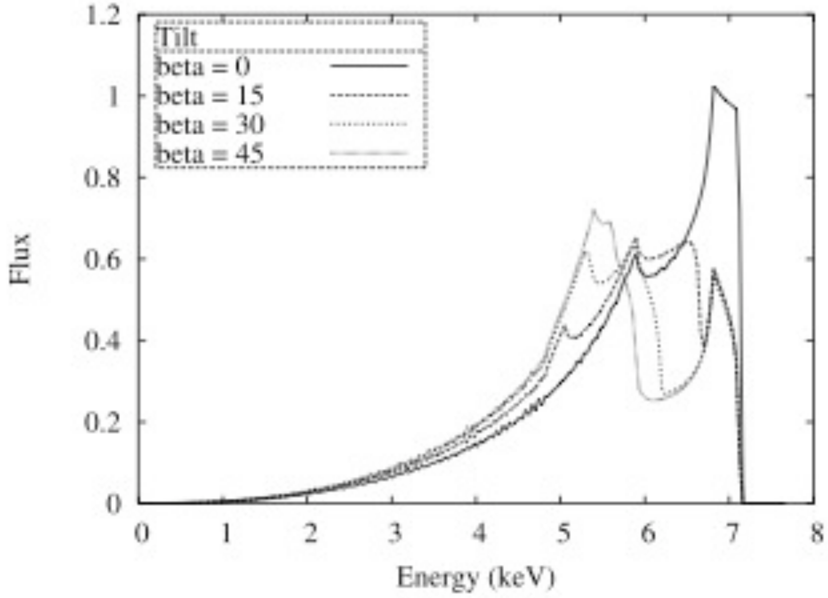


FIG. 2.—Synthetic line profiles for a sample of two-component Bardeen-Petterson disks with $r_{BP} = 15r_g$ and various values for the tilt β in the range $0 \leq \beta \leq 45^\circ$. The observer is located at $\phi_0 = 90^\circ$ and maintains a constant inclination of $i_{out} = 45^\circ$ with respect to the outer disk. [*See the electronic edition of the Journal for a color version of this figure.*]

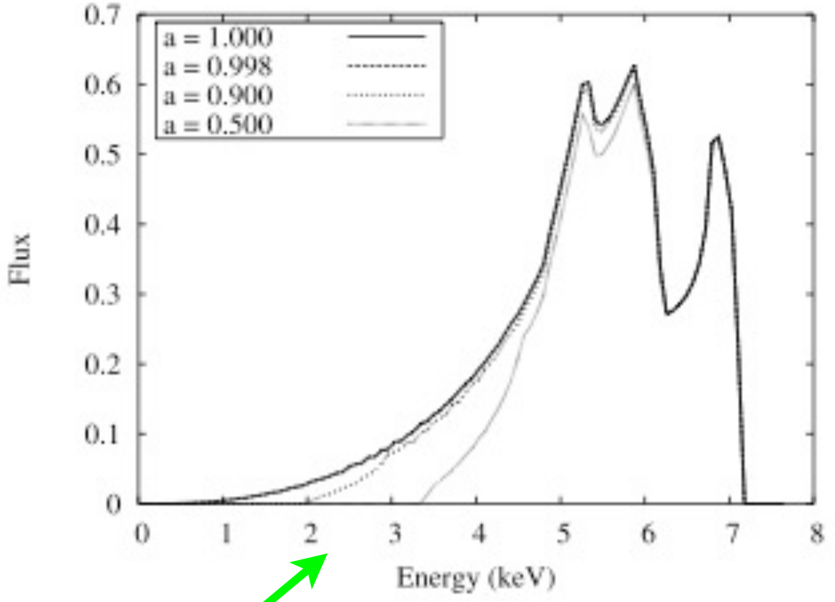


FIG. 4.—Synthetic line profiles with the tilt, transition radius, longitude of the observer, and inclination of the observer relative to the outer disk fixed at $\beta = 30^\circ$, $r_{BP} = 15r_g$, $\phi_0 = 90^\circ$, and $i_{out} = 45^\circ$, respectively. The emissivity assumes a form $\epsilon(r) \propto r^{-q}$, with $q = 2.5$. The spin of the black hole is varied over the range $0.5 \leq a/M \leq 1$. [*See the electronic edition of the Journal for a color version of this figure.*]

Fragile et al. 2005

The B-P disk line profile is not very sensitive to spin a

Iron line profiles of Bardeen-Petterson disks

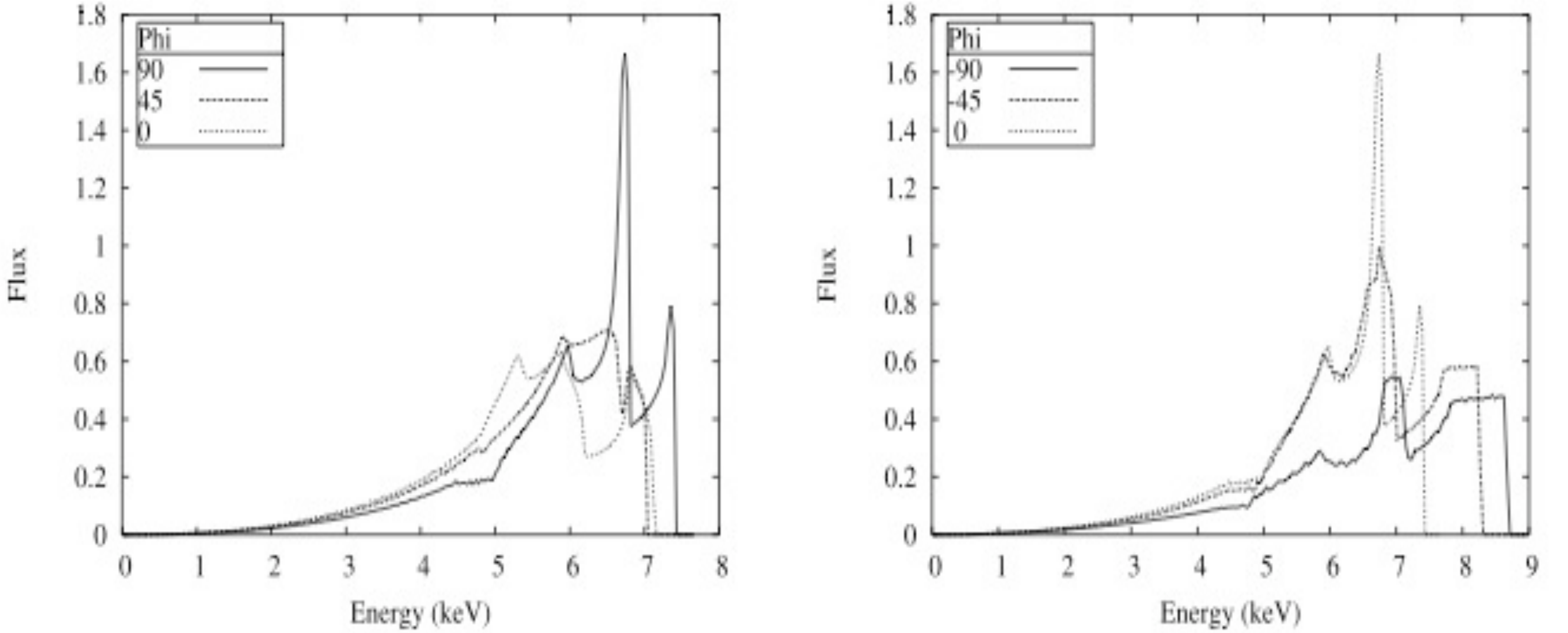


FIG. 5.—Synthetic line profiles with the tilt, transition radius, and inclination of the observer relative to the outer disk fixed at $\beta = 30^\circ$, $r_{\rm BP} = 15 r_g$, and $i_{\rm out} = 45^\circ$, respectively. The longitude of the observer is varied over the range (*a*) $0 \le \phi_0 \le 90$ and (*b*) $-90 \le \phi_0 \le 0$ [*See the electronic edition of the Journal for a color version of this figure.*].

Fragile et al. 2005

Multiple or triple-peaked line profile often shows up !

- signature of BP disks

in contrast: double or blurred line profile seen in AGNs

Reverberation mapping with the iron lines due to illuminating X-ray flares

- proposed for the study of the iron line response to the illuminating flares in AGNs (before the Chandra era)
- model based on hard X-ray irradiation of cold, dense matter in the innermost disk inside ~ 100 Rg
- broad, relativistic iron lines to probe black hole mass and spin

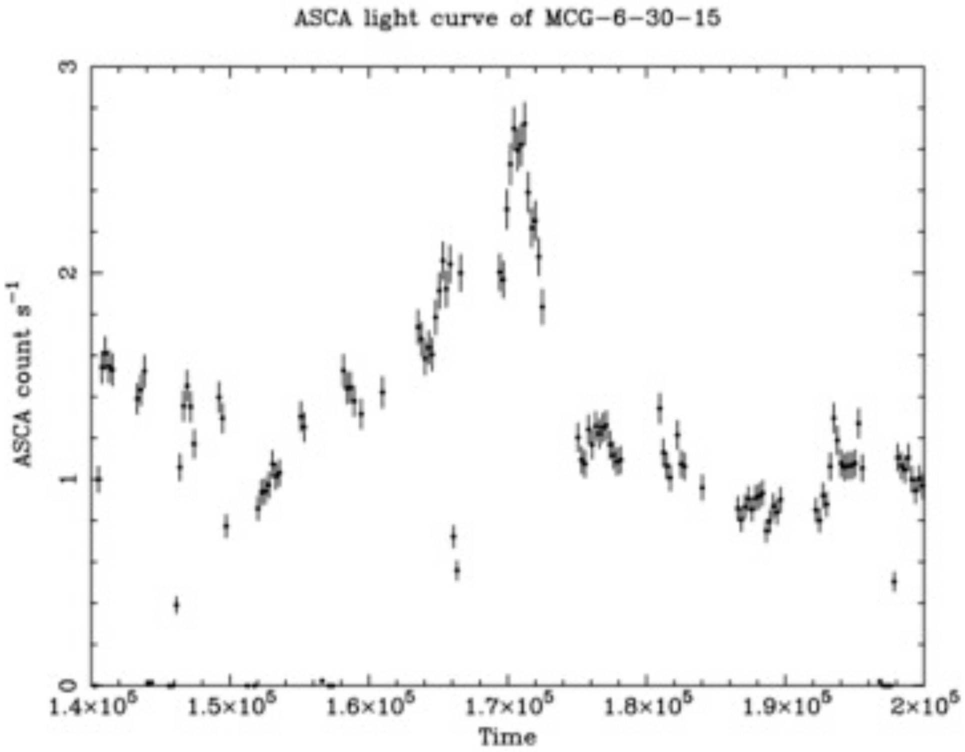


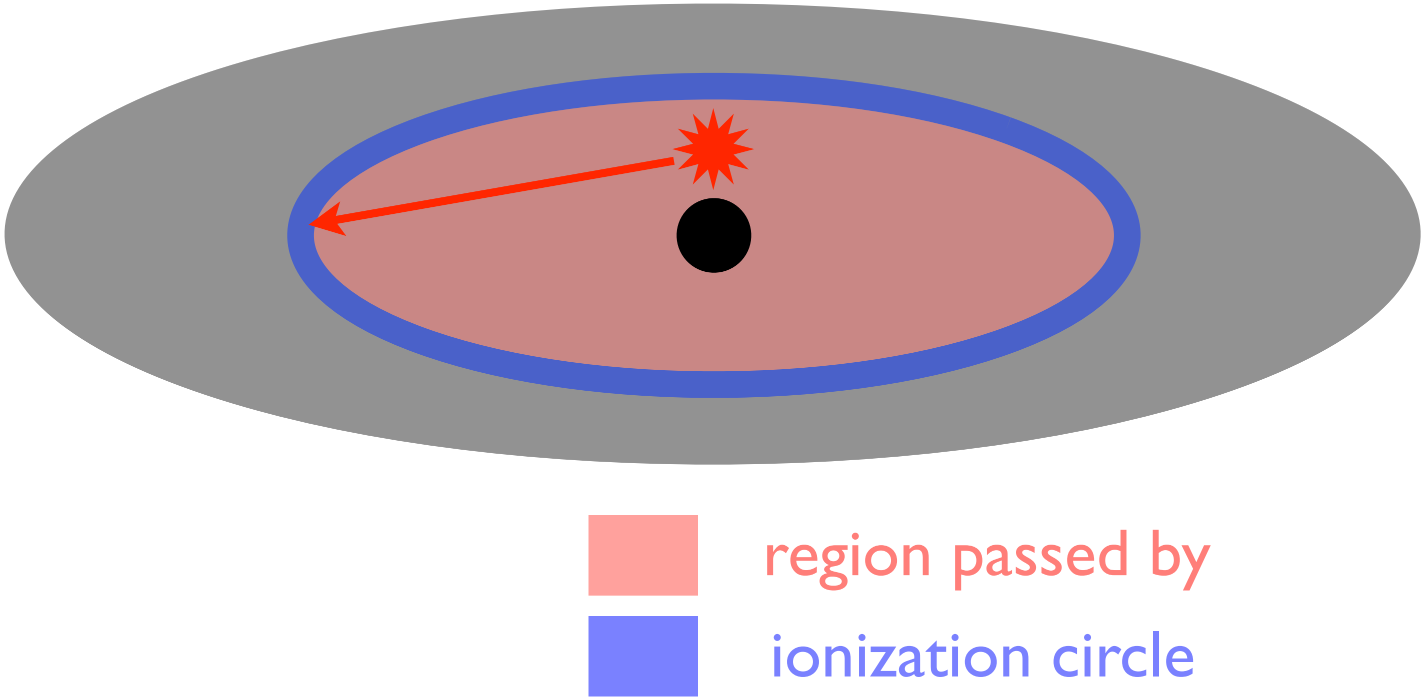
FIG. 1.—The 60,000 s *ASCA* light curve of MCG −6-30-15 showing two "flares" lasting a few thousand seconds each (Lee et al. 1999).

Young & Reynolds 2000

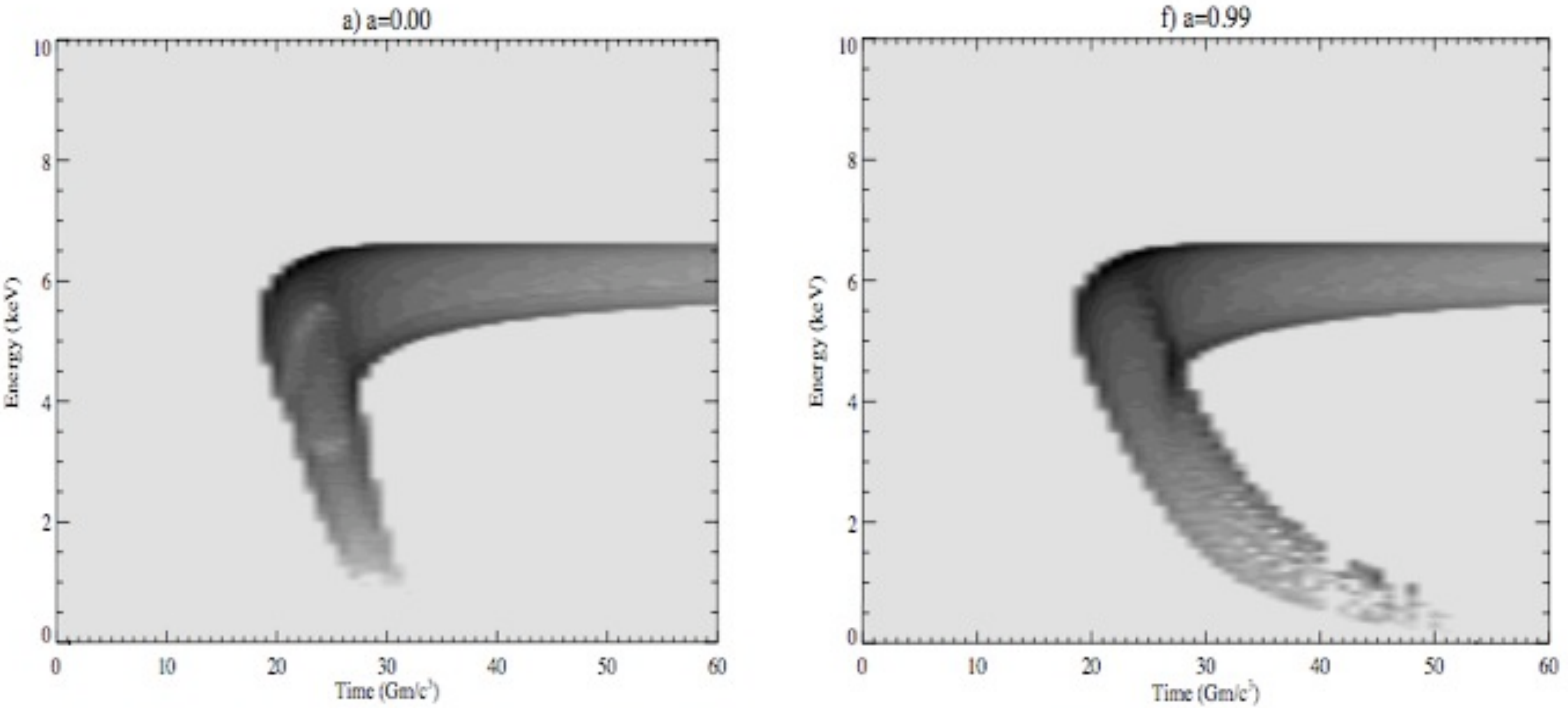
A δ-function illumination flare:

generating an expanding ionization circle

- A circle of illumination in the rest frame
- expanding with light speed

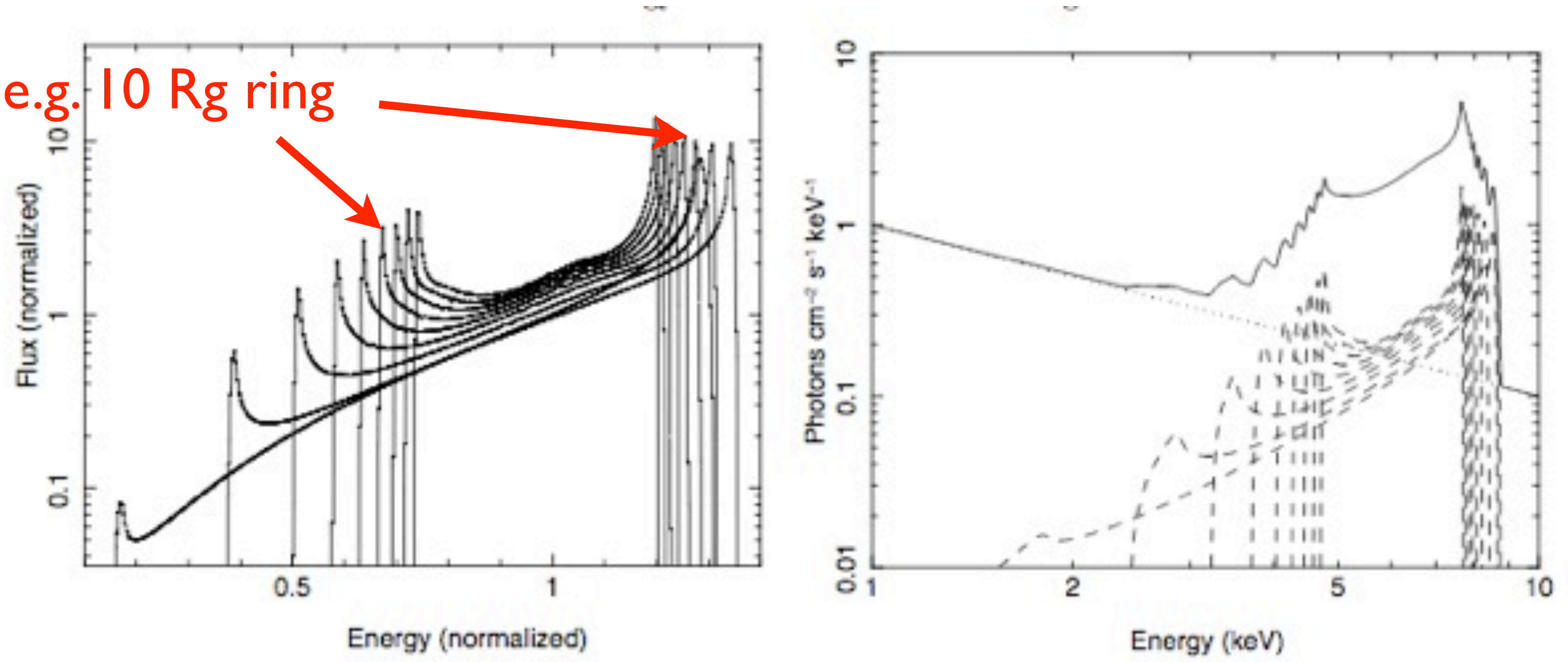


Evolution of Iron line profile from an expanding ionization circle



Young & Reynolds 2000

line profile from an ionization circle/ring



e.g. 10 Rg ring

Figure 1. Forming a double-horn spectral line by superposing profiles of several narrow-rings. Left: theoretical profiles from a set of nine infinitesimally narrow rings orbiting in the equatorial plane of a Kerr black hole. Radii of the rings increase equidistantly from $r = 2$ to $r = 18$ gravitational radii. Broader and more redshifted profiles correspond to smaller rings, which rotate at faster speed and reside deeper in the gravitational well. Energy is normalized to the unit rest energy of the line; each profile then extends from $g_{\rm min}$ to $g_{\rm max}$ for its corresponding parameters. Background continuum is subtracted. Right: as on the left, but with rings of a small (finite) radial extent of $\Delta r = 1$. The rest energy of the line is set to 6.4 keV and a power-law continuum added to reflect the fact that line profiles in real spectra are obtained by considering the proper underlying continuum. Dashed lines denote the individual components forming the prototypical spectrum; the latter is shown by the solid line. The signature of the individual rings is visible in the wings of the final profile. The common parameters of both plots are: observer inclination 75° (i.e. close to the edge-on view), black hole spin $a = 0.998$ (prograde rotation).

A characteristic double-horn profile dominated by photons having energy around the maximum or the minimum of the allowed range

Karas et al. 2010

Reverberation mapping: Schwarzschild BHs

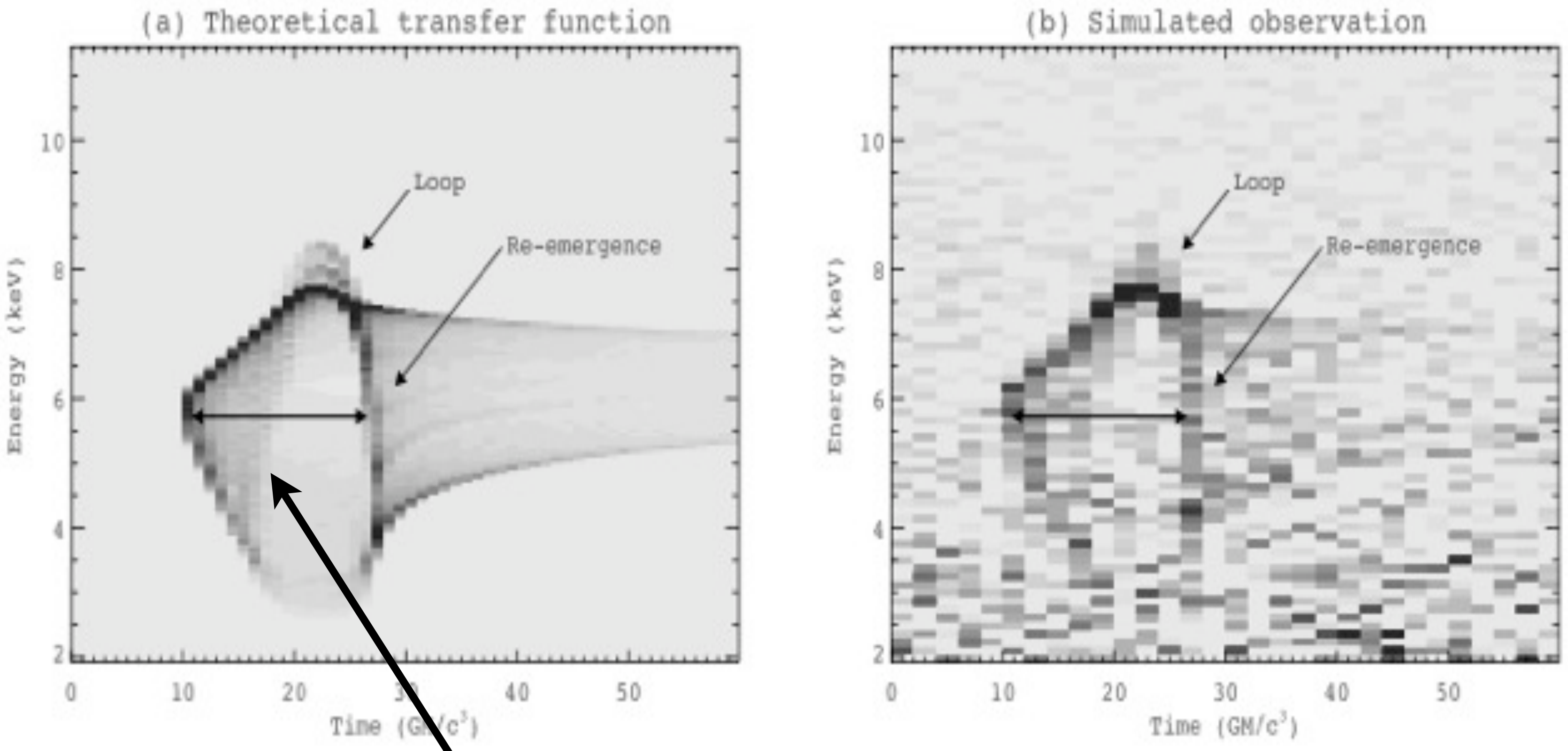


FIG. 6.—Panel *a* shows the theoretical transfer function for a Schwarzschild case with an inclination of 60° and an on-axis flare at a height of $10GM/c^2$. Note the "loops" in the transfer function corresponding to fluorescence from the ionized regions of the disk within the innermost stable orbit. The horizontal line shows the time delay between the initial response and the "reemergence" which may be used to estimate the black hole mass. Panel *b* shows the simulated observed transfer function. The loops are still visible. The data have been rebinned to produce these figures with improved signal-to-noise ratio.

part of the ionization circle is seen because of light travel effect

Young & Reynolds 2000

Separation between the double line peaks become narrower with time due to 1) reduced gravitational redshift 2) reduced Doppler effect

Reverberation mapping: Kerr BHs

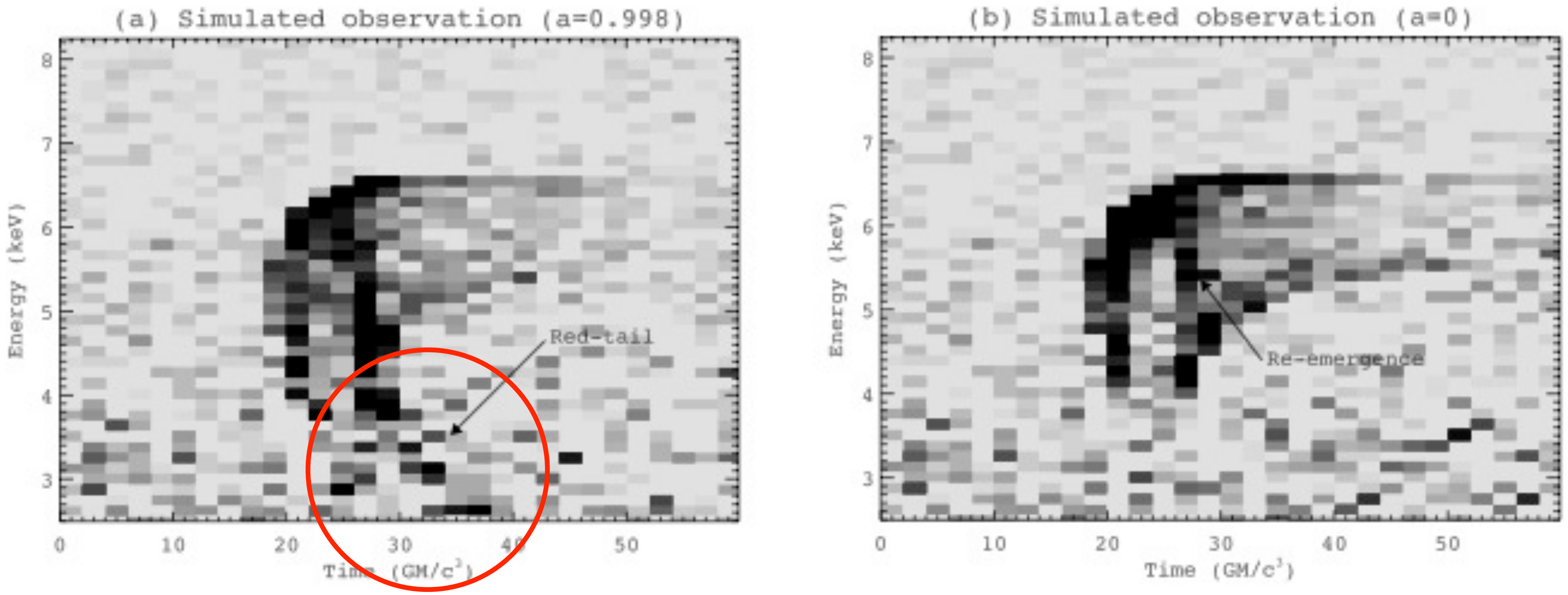


FIG. 4.—Simulated transfer function for (*a*) an extremal Kerr hole and (*b*) a Schwarzschild hole. In both cases, the flare has been placed on the symmetry axis at a height of $10GM/c^2$ above the disk plane, and an observer inclination of 30° has been assumed. The data have been rebinned to produce these figures with improved signal-to-noise ratio.

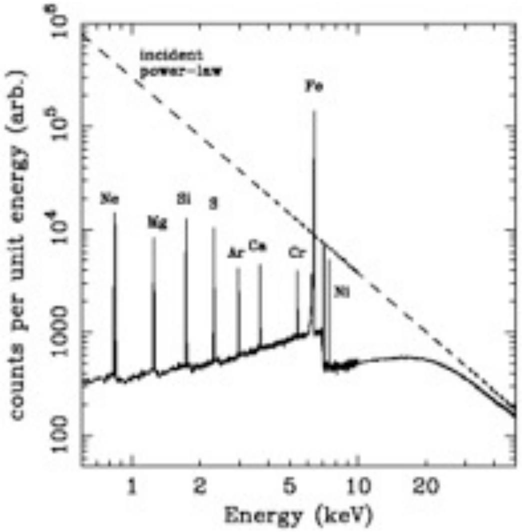
different from the Schwartzchild BH case:

A "red-ward moving bump"

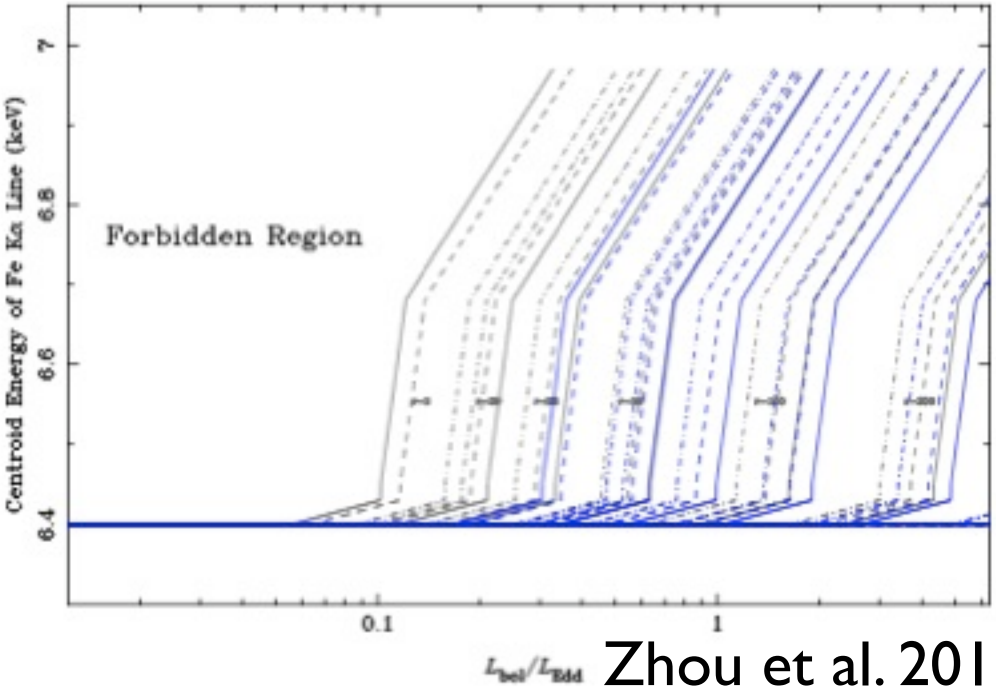
Young & Reynolds 2000

Focus on the iron line in AGNs

- incident power-law component irradiates the cold disk
- the accretion disk is ionized, generating the disk lines
- Iron line is the strongest; details depend on the ionization state



X-ray reflection from an illuminated slab



Zhou et al. 2010

Figure 1. Predicted line energies in the $(E_\alpha, \lambda_{\rm Edd})$ plane. The black lines are the results for a Schwarzschild BH; the blue lines are for a maximally spinning astrophysical BH. In each case, we repeated the calculation for six values of r (indicated as labels next to the Schwarzschild curves), and three values of $h = 5r_{\rm g}$, $8r_{\rm g}$, and $15r_{\rm g}$. For each r value, the three corresponding h curves are plotted as solid, dashed and dot-dashed lines, respectively.

Iron disk lines will form in a large luminosity range including super-Eddington regimes

Iron line reverberation mapping of the innermost disks
AGNs vs. Previously dormant SMBHs (TD flares)

AGN

- Coupling between the iron line and the ionization flux
- Illuminations by both persistent flux and flares exist !
- Only recently results are obtained by averaging flares

TD flares

- a newly formed disk has not been ionized
- X-ray flare illuminates and ionized the fresh disk
- Rising edge of the luminous TD (X-ray) flare serves as the “δ-function” illumination

TD flares from previously dormant SMBHs are perfect targets

Tidal Disruption Events: Swift J2058

Z ~ 1.185

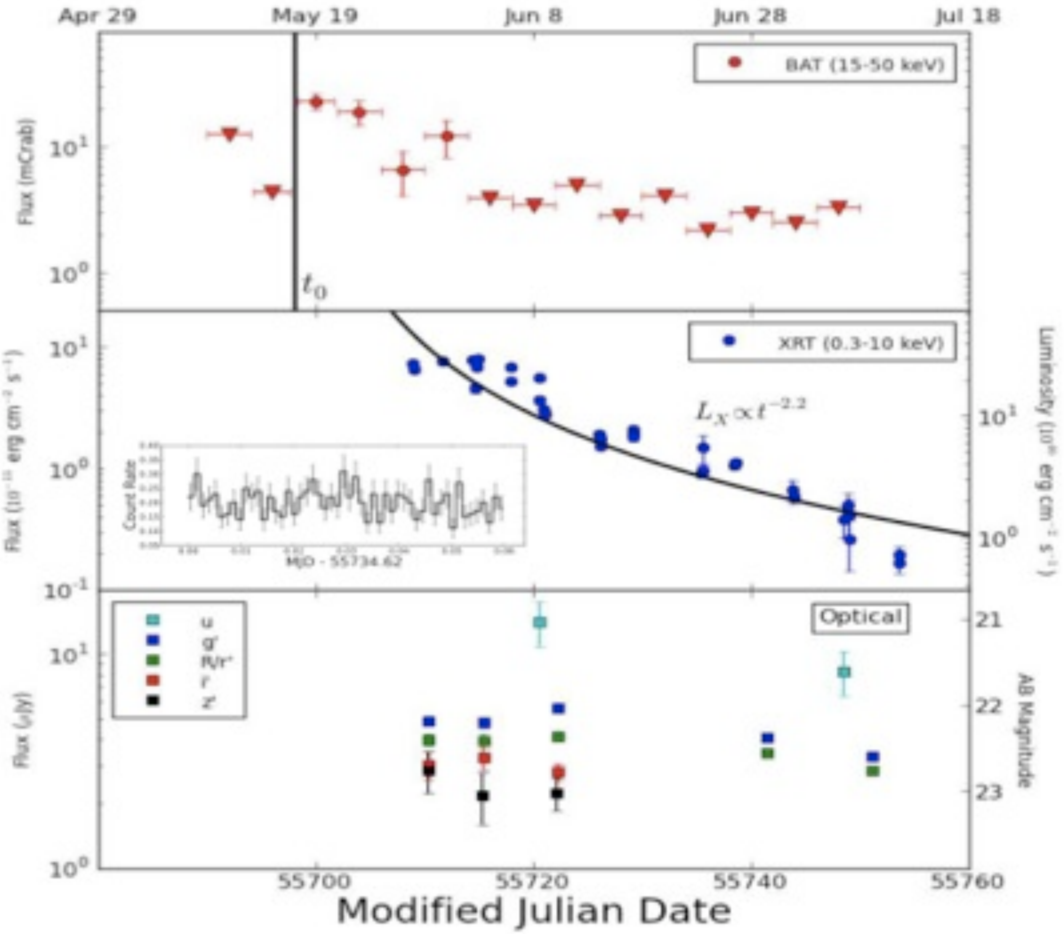


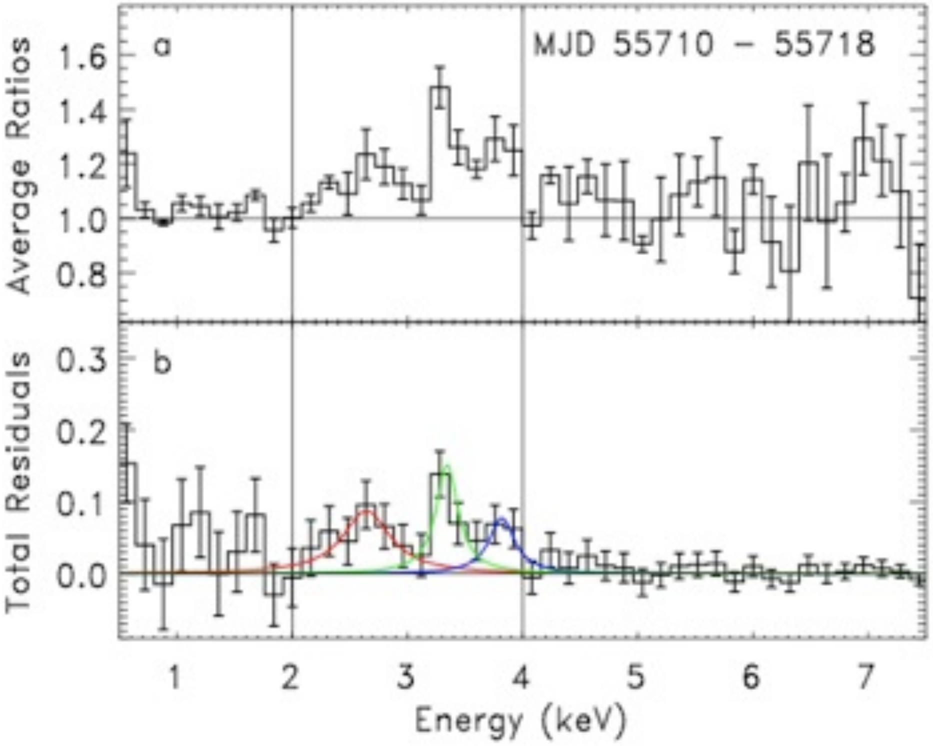
FIG. 1.— Hard X-ray (15–50 keV), X-ray (0.3–10 keV), and optical light curve of *Sw J2058+05*. The inset in the X-ray panel plots our *Chandra*-HRC ToO observation (0.1–10 keV). Inverted triangles represent 3σ upper limits.

Similar to Swift J1644: a long-lived, super-Eddington event, luminous radio counterpart, faint optical emission

see Cenko et al. 2012, but out mass estimate is different (see below)

X-ray observations Swift J2058

- triple-peaked lines probably due to highly ionized line Fe XXVI at around 7.0 keV; line flux gives the lower limit on M_{BH}: ~10^8 solar masses
- probably detection of the Bardeen-Petterson disk, R_{BP} ~ a few tens Rg
- implying a spinning SMBH



Yu & Zhang, 2012, submitted

Average results of the first few observations

~ 6 sigma & 8 sigma

Z = 1.185

Conclusions

- We have detected complex line emission from Swift J2058, which we interpret as a triple-peaked iron line from an innermost warping disk (line emission first occurred ~ 10 days after the first detection)

- The evolution of the line profile is consistent with that the line emission from an expanding ionization circle in a Bardeen-Petterson (BP) disk. The line profile maps the gravitational field in relation to the distance to the BH. The SMBH is therefore a spinning SMBH.

- Simple modeling of the data gives the SMBH mass of the order of 10^9 solar masses (then L_{peak} ~ a few times L_E measured on time scales shorter than the dynamic time scales at the ISCO), but lower SMBH mass can be obtained if assuming slower expansion. *This is larger than the SMBH mass expected for TD of giant stars for non-spinning SMBH, but a rapidly spinning SMBH up to 7x10^8 solar masses would allow TD flares for sun-like stars (Kesden 2012)* - **An extraordinary massive SMBH would explain its uniqueness among TDEs.**

- Line spectroscopy (not limited to iron line) during the very early stages of TD flares is essential for probing the SMBH spin and the innermost flow with the Bardeen-Petterson effect - good to know for future missions targeted at TD flares.