supermassive black hole binaries as
multimessenger sources:

PROPERTIES OF SMBHB X-RAY SPECTRA

JULIE MALEWICZ

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LAURA BRENNEMAN
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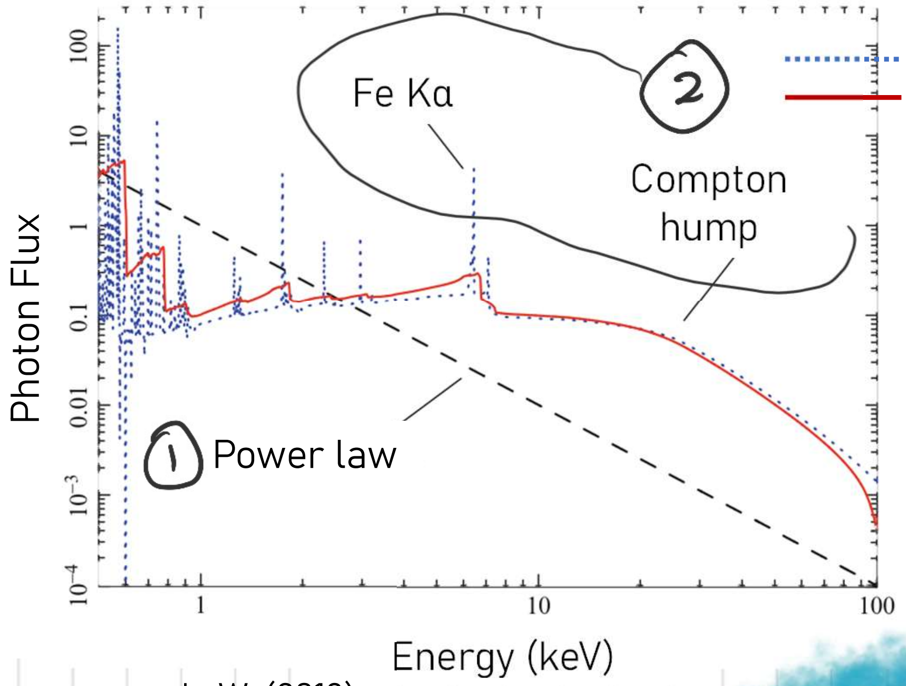
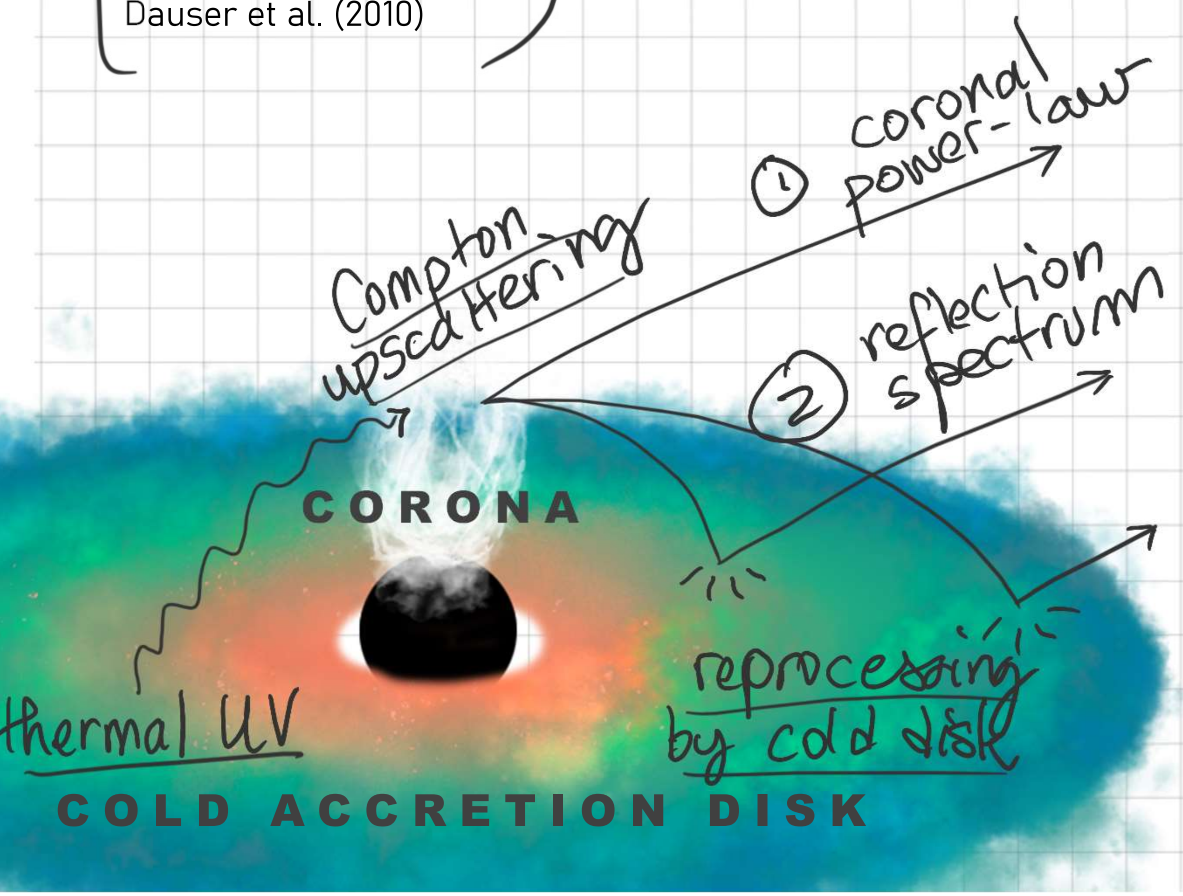


Emission profile computed using xillver, convolved with relativistic blurring kernel relconv

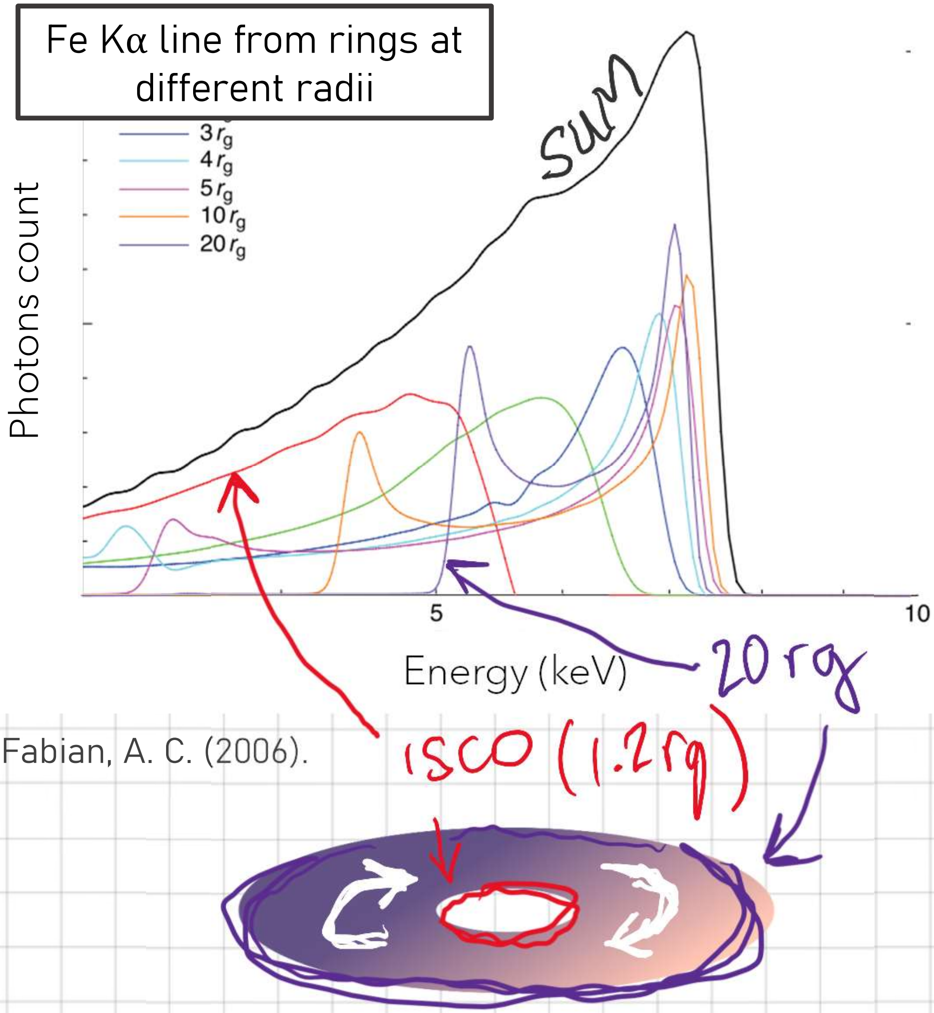
(García and Kallman (2010)
Dauser et al. (2010))

Brenneman, L. W. (2013).

Reflection **SPECTRUM** for a neutral **ACCRETION DISK**



IRON LINE IN BH SPIN STUDIES

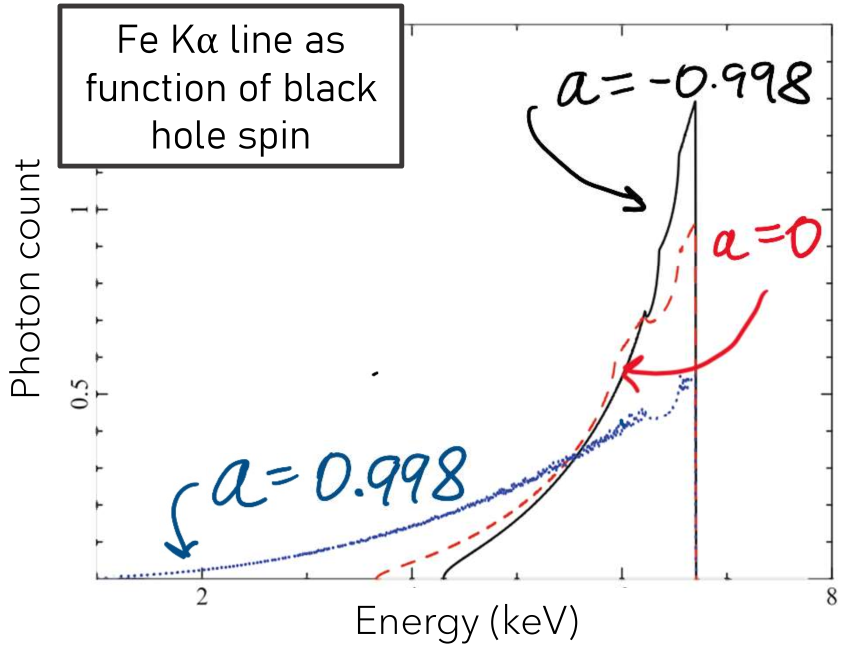


Fe Kα line from rings at different radii

Fabian, A. C. (2006).

DUAL PEAKED >> relativistic Doppler from disk rotation

SMEARED >> gravitational redshifting

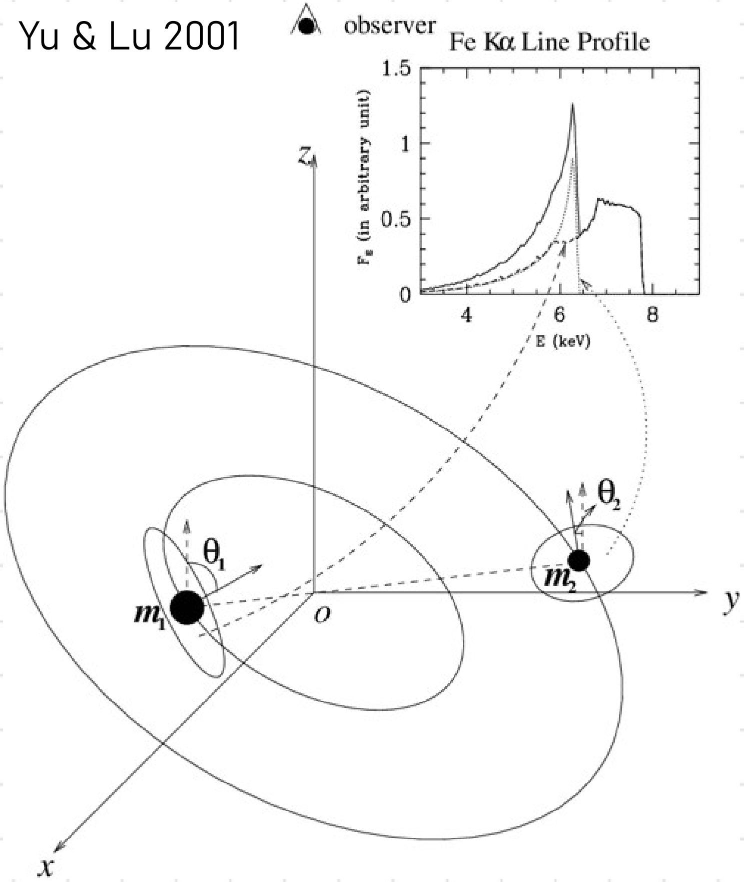


Fe Kα line as function of black hole spin

Brenneman, L. W. (2013).

Fe-Kα PROFILE in limited SMBH BINARY configurations

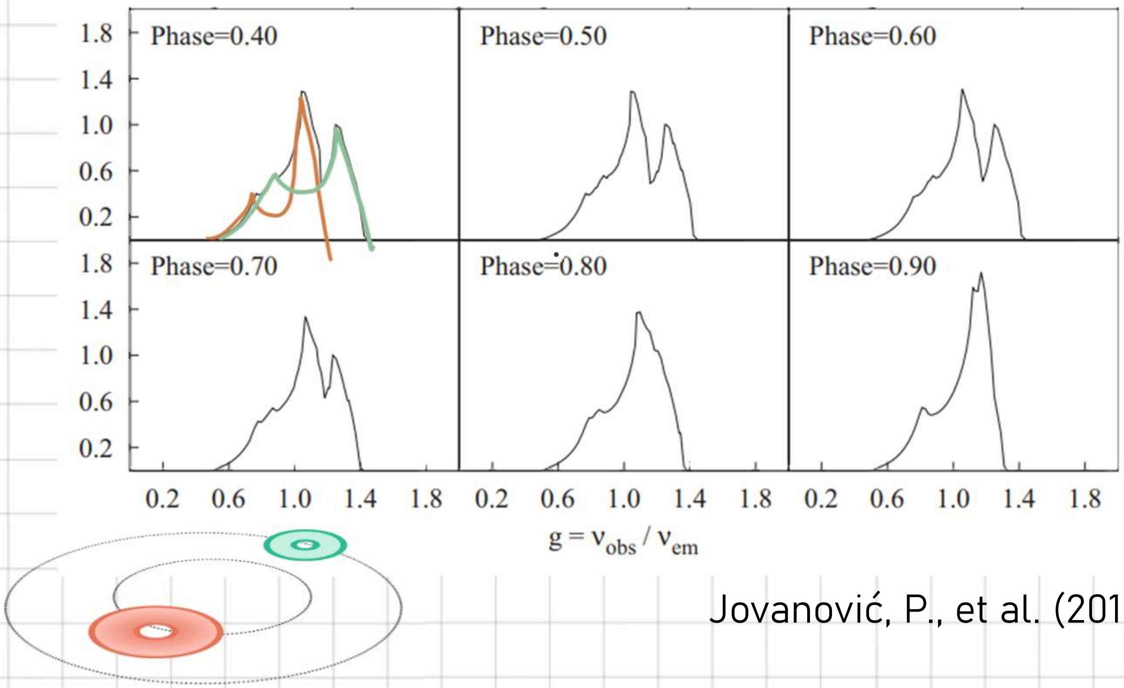
Yu & Lu 2001



See also:

Sesana et al. 2012
McKernan et al. 2013

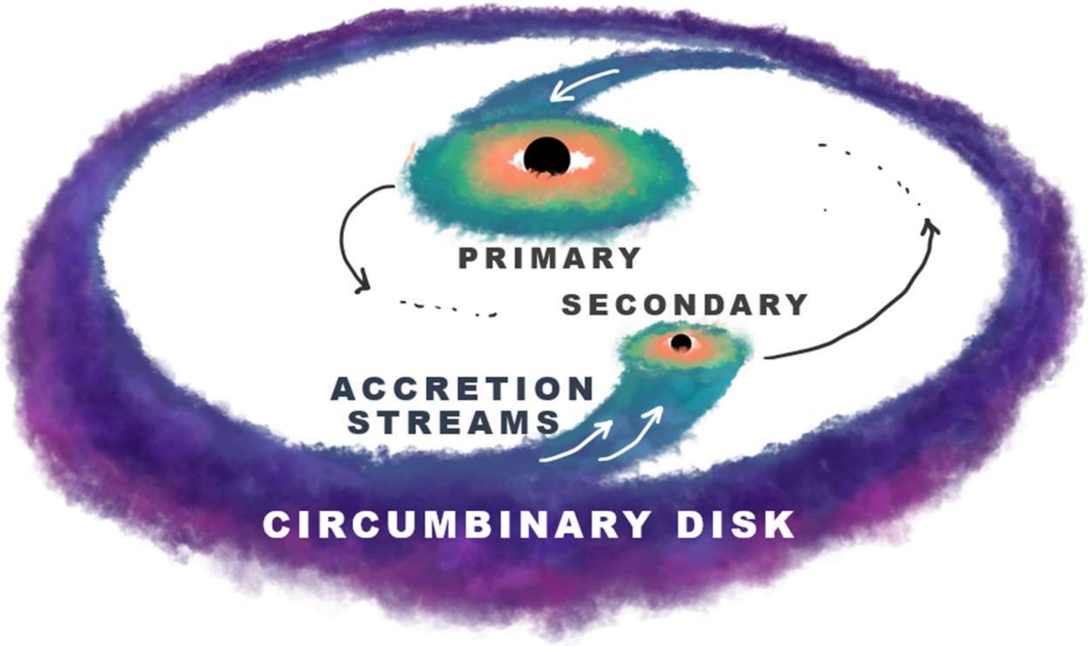
Phase dependence of Fe line profile in an **EQUAL MASS BINARY**



Jovanović, P., et al. (2014)

Seeing double:

EXTENDING THE FRAMEWORK TO BINARIES



With leading binary effects:

ORBITAL DOPPLER >> periodic opposite Doppler shift due to orbital motion

ACCRETION INVERSION >> smaller BH accretes more rapidly, leading to super-Eddington, over-ionized regimes

ACCRETION AND IONIZATION

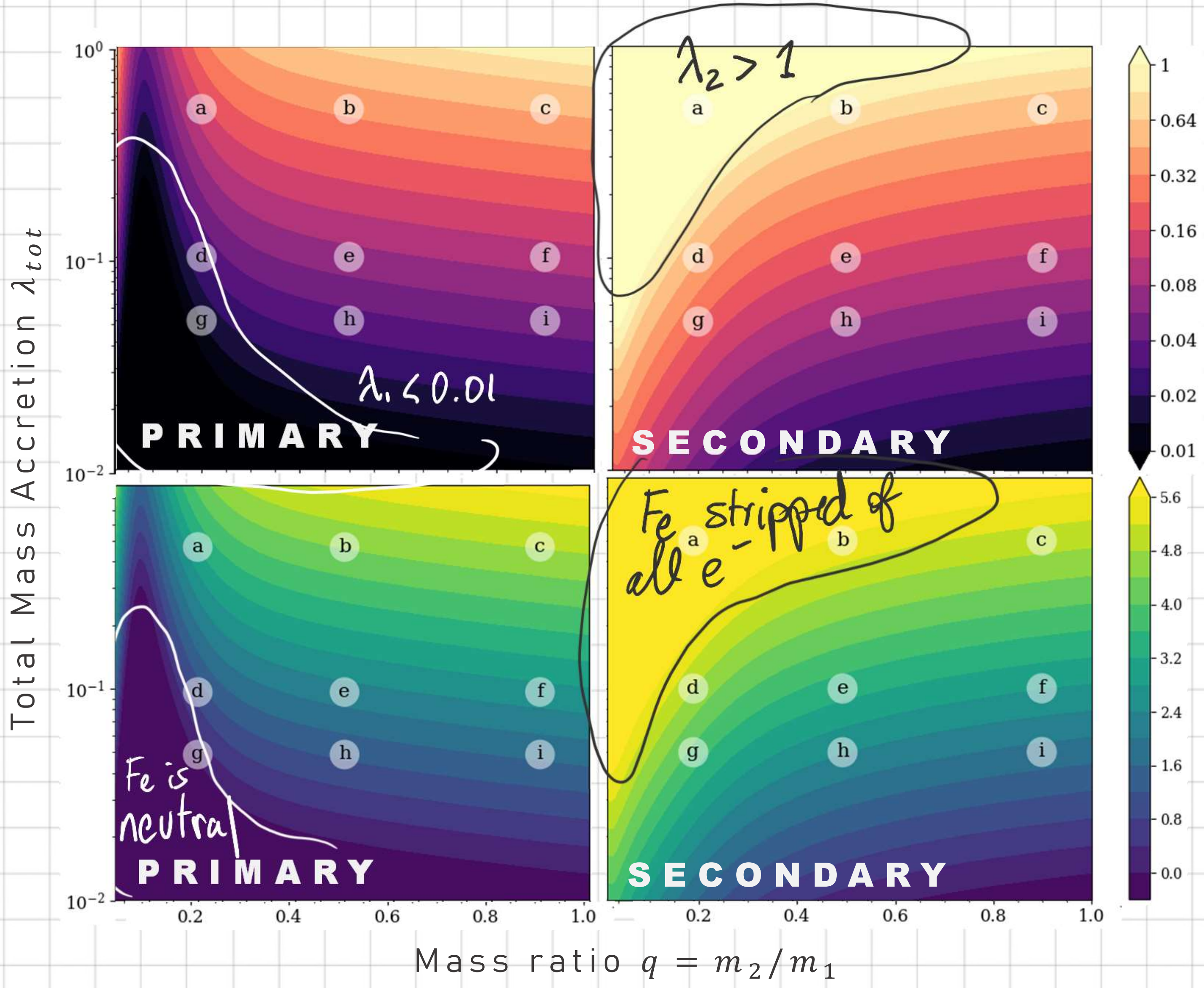
for varying q and λ_{tot}

MASS ACCRETION

$$\lambda_{tot} = \frac{\dot{M}}{\dot{M}_{Edd}}$$

PEAK IONIZATION

$$(\xi \propto \rho^{-1} F_X)$$



Malewicz et al (2024, in prep).

COMPOSITE SPECTRA

for varying q and λ_{tot}

`phabs*relxilllpCp`

phase = 90°

inclination = 30°

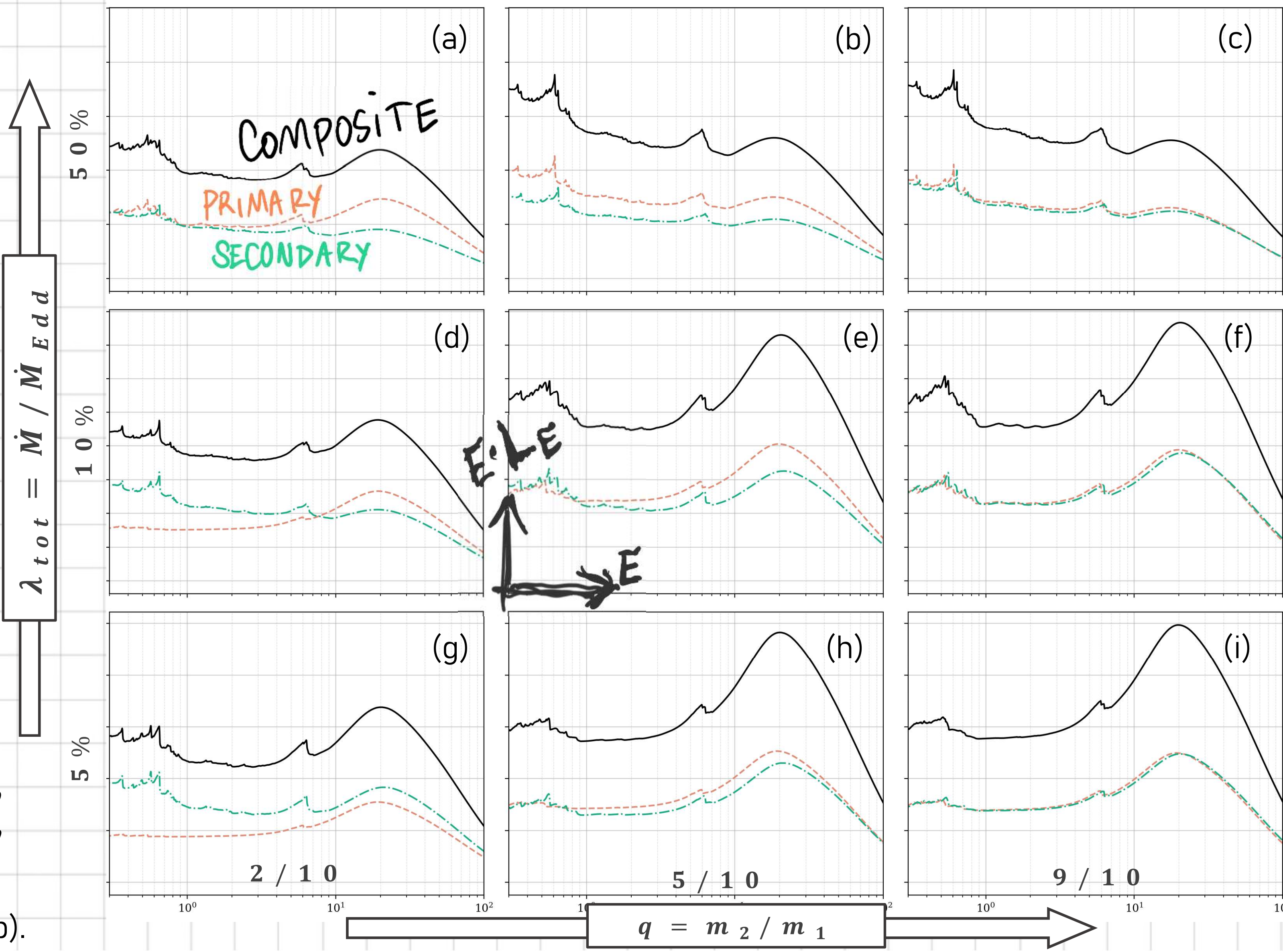
spins = 0.99

corona height = $10\ r_g$

α-disk gradient for ionization and density

Note: every row has different y limits,

But we're interested in the morphology of the spectra



Malewicz et al (2024, in prep).

OBSERVATIONAL PROSPECTS

- We conduct a feasibility study by convolving our model spectra with next-gen X-ray telescope instrument response

i.e. we simulate what a telescope would see when looking at our binary

NASA's AXIS

ESA's ATHENA

(shelved for now)

HEX-P
HIGH ENERGY X-RAY PROBE

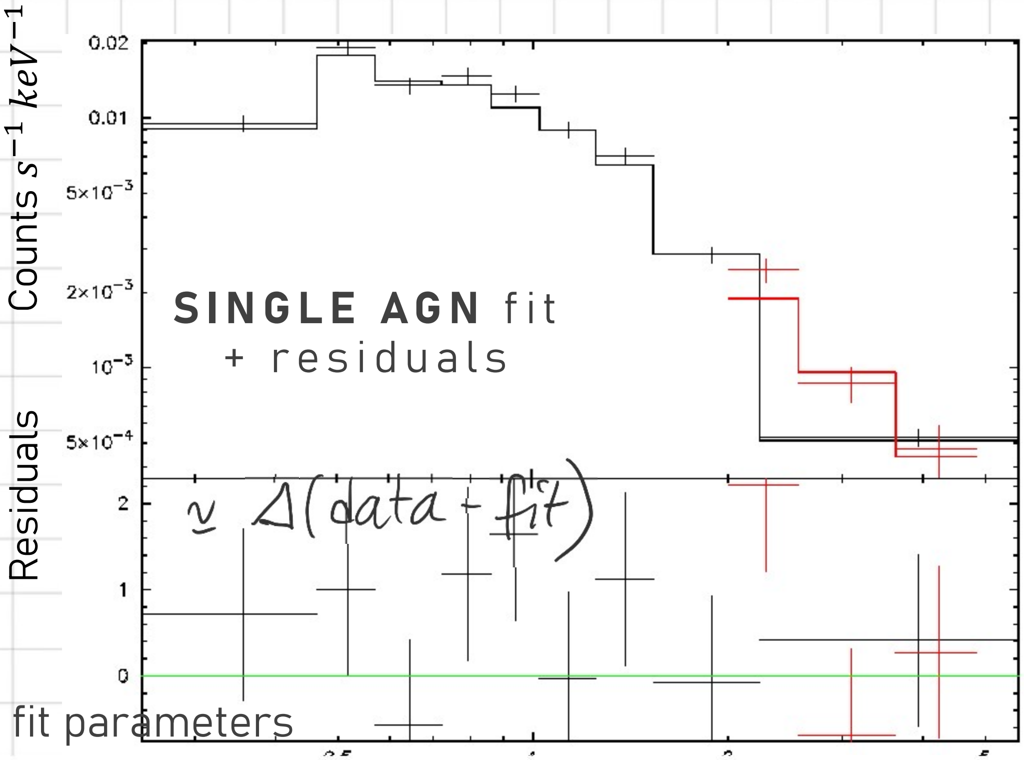
STROBE-X

- We then force-fit a single BH reflection model (relxill) and identify where the points of friction are

i.e. we look for binary signatures!

SIMULATED OBSERVATIONS

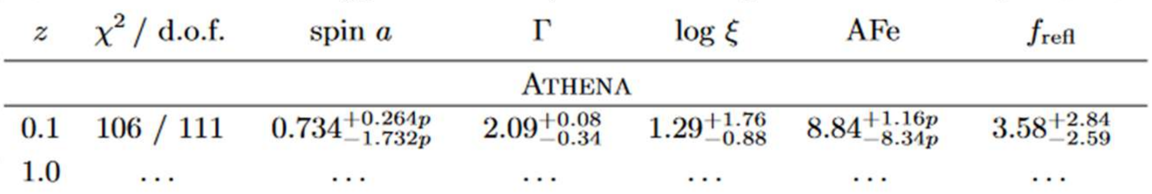
by **ATHENA** of $10^6 M_\odot$ binary at $z = 0.1$



SINGLE AGN fit
+ residuals

$\simeq \Delta(\text{data} - \text{fit})$

fit parameters



z	χ^2 / d.o.f.	spin a	Γ	log ξ	AFe	$f_{\rm refl}$
			ATHENA			
0.1	106 / 111	$0.734^{+0.264p}_{-1.732p}$	$2.09^{+0.08}_{-0.34}$	$1.29^{+1.76}_{-0.88}$	$8.84^{+1.16p}_{-8.34p}$	$3.58^{+2.84}_{-2.59}$
1.0	…	…	…	…	…	…

- Overall, at $10^6 M_\odot$, those are **faint** sources
- Not viable $z > 0.1$

Notes on the fit:

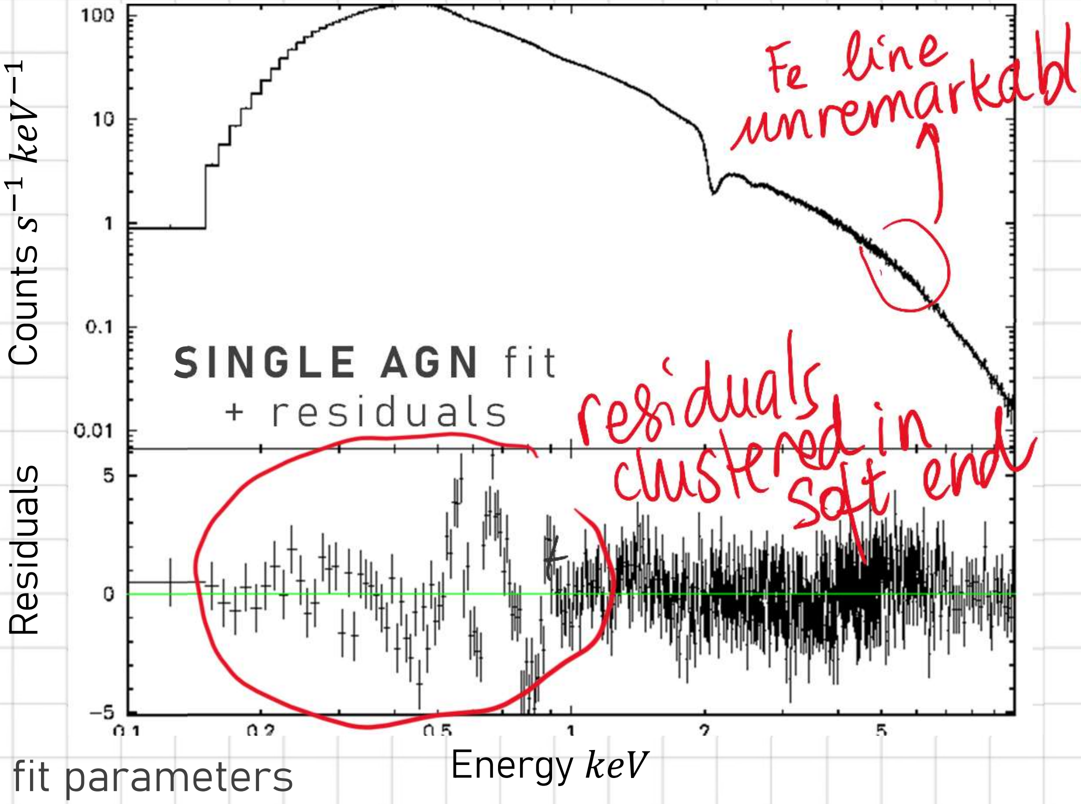
- Statistically "good" fit (reduced $\chi^2 < 1$)
- **Spin** completely unconstrained

Malewicz et al (2024, in prep).

SIMULATED OBSERVATIONS

by **AXIS** of $10^9 M_\odot$ binary at $z = 0.1$

PTA-type source for comparison



SINGLE AGN fit
+ residuals

Fe line unremarkable

residuals clustered in soft end

fit parameters

- On brighter sources, residuals are mainly on the **soft end**
- **Fe line unremarkable**

Malewicz et al (2024, in prep).

TAKEAWAYS

email jlm@gatech.edu for any questions!

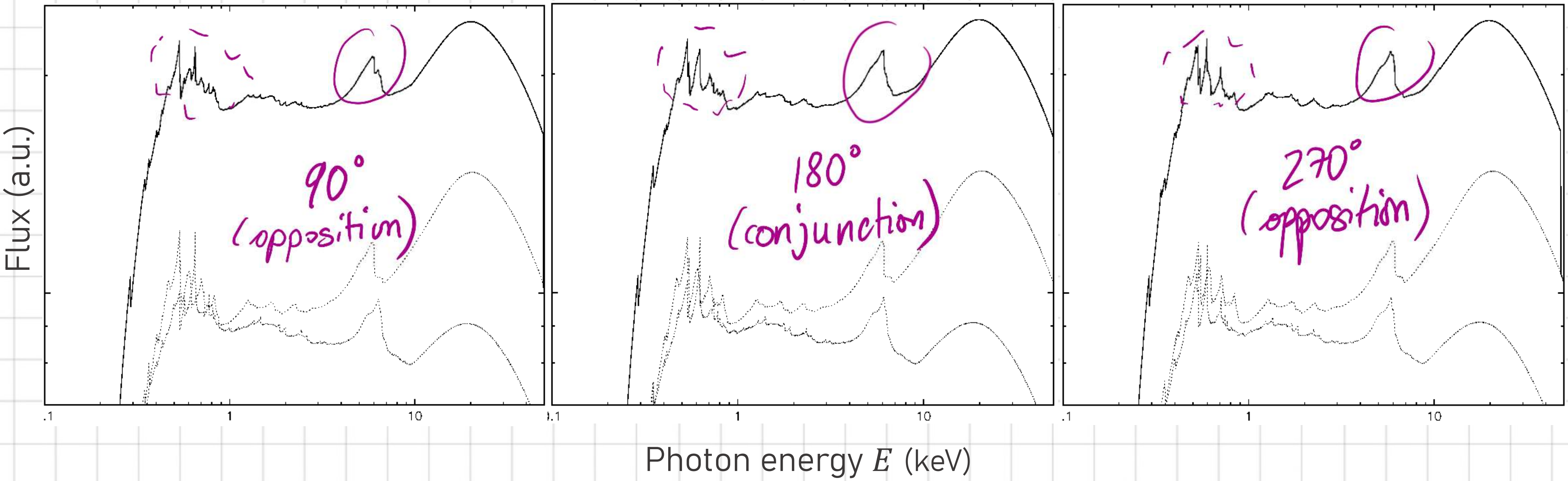
- **Bifurcation in accretion and ionization properties** in both BHs turn an already highly degenerate parameter space into a few very different spectral morphologies and many different observational outcomes
- Unless the source is close-by ($z{\sim}0.1$), it will be **hard to resolve** anything within the canonical 100 ks exposure time
- Other complication is the **short orbital period**: no time-resolved spectra, the result will be **smeared** and won't appear periodical

- Some **unexpected binary indicators** (incl. simple bad fits, low or unconstrained spins due to anomalous iron line, or fit residuals clustered in soft end, etc)

Overall, not a slam-dunk, but clear avenues for further exploration if we are willing to put in the **time** and **effort** (observational campaigns with longer exposure and working with the PTAs to tackle brighter sources)

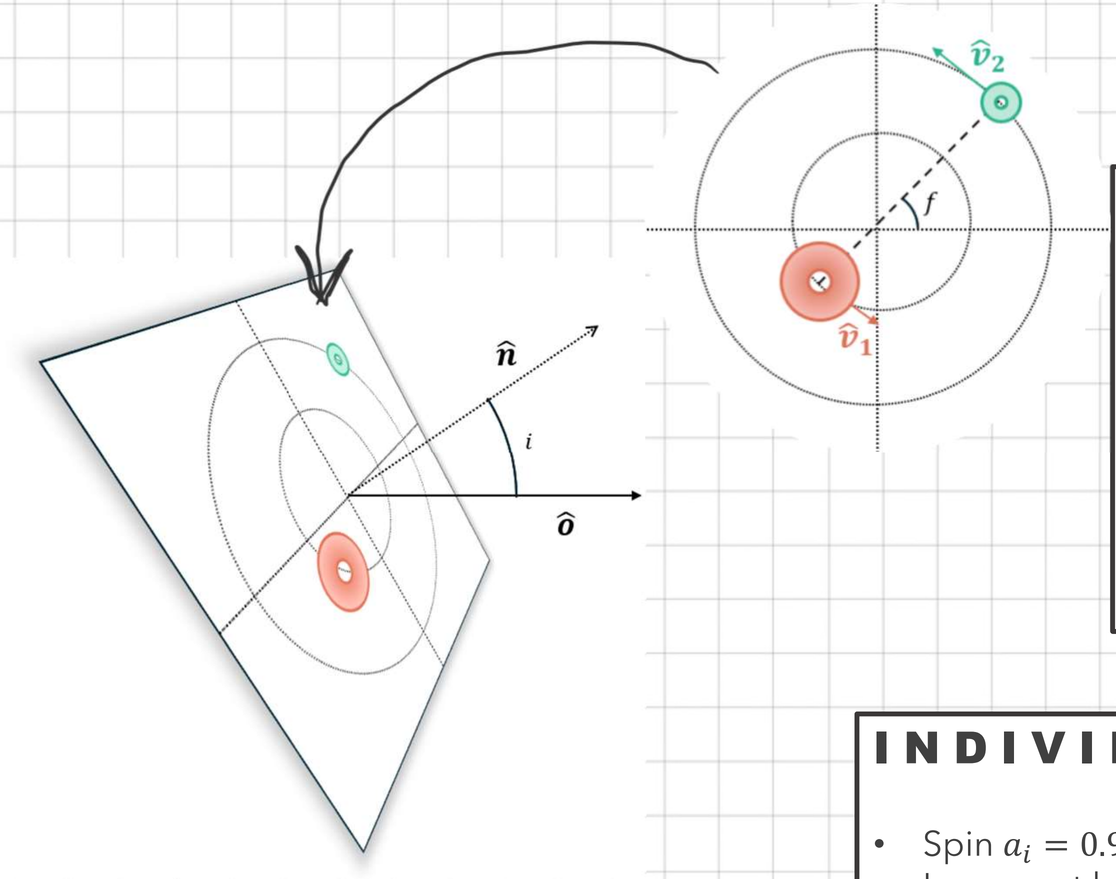
ORBITAL REDSHIFT

for q = 0.2 and $\lambda_{tot} = 10\%$ binary



Doppler shift most visible in narrow features,

BUT LISA binaries have short orbital periods, so time-resolved observations are not possible



BINARY

- Mass $M = 10^6 M_\odot$ or $10^9 M_\odot$
- Mass ratio $q = 0.2, 0.5$ and 0.9
- Mass accretion rate $\lambda_{tot} = 5\%$, 10% or 50% of Eddington
- Orbital separation $s = 100\ r_g$
- Inclination $i = 30°$
- Orbital phase $f = 0°, 90°, 180°, 270°$
- Redshift $z = 0.1$ or 1.0

INDIVIDUAL BHS

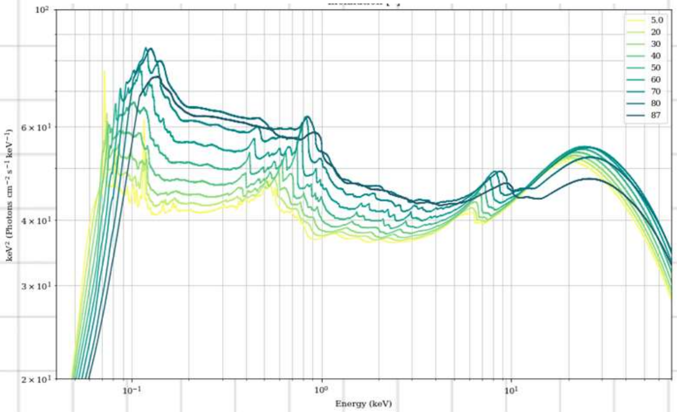
- Spin $a_i = 0.99$
- Lamppost height $h_i = 10\ r_g$
- Disk bounds = ISCO to tidal truncation radius $q, s \rightarrow r_{out,i}$
- Mass accretion rates = mass ratio-dependent $q \rightarrow \lambda_i$
- Ionization = α-disk gradient from lamppost $\lambda_\mathrm{i} \rightarrow \log \xi_i(r)$

SIMPLIFYING ASSUMPTIONS

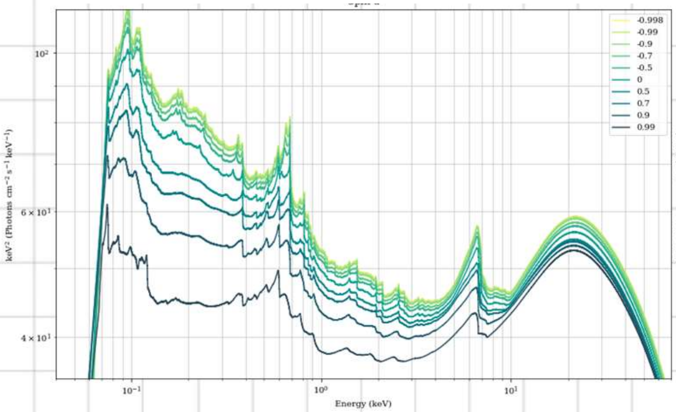
- Circular & coplanar
- No X-ray emissions from circumbinary disk or from accretion streams

VARYING PARAMETERS

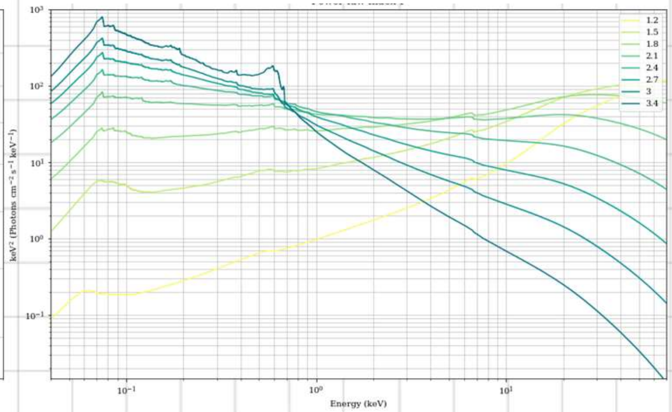
INCLINATION i



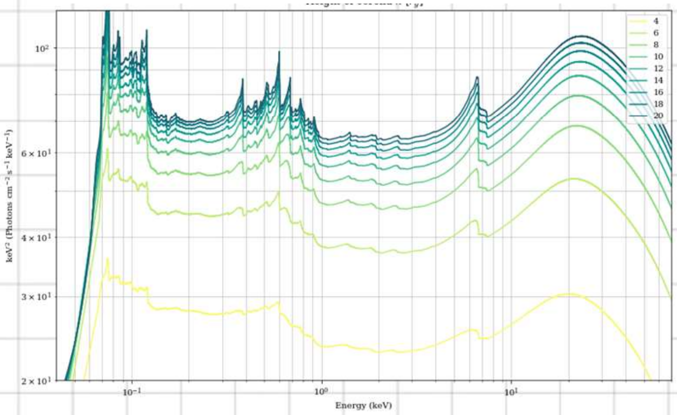
SPIN a



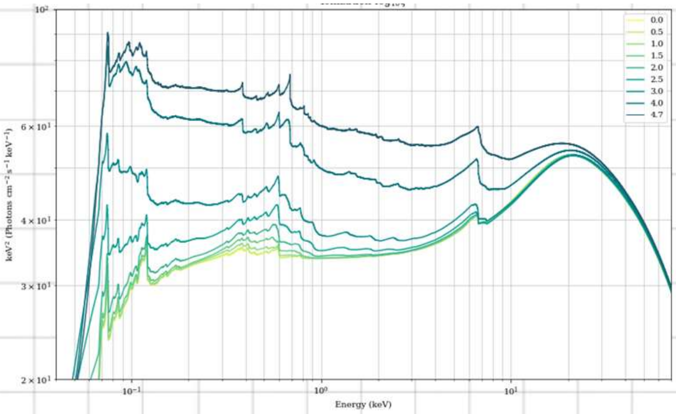
POWER LAW index Γ



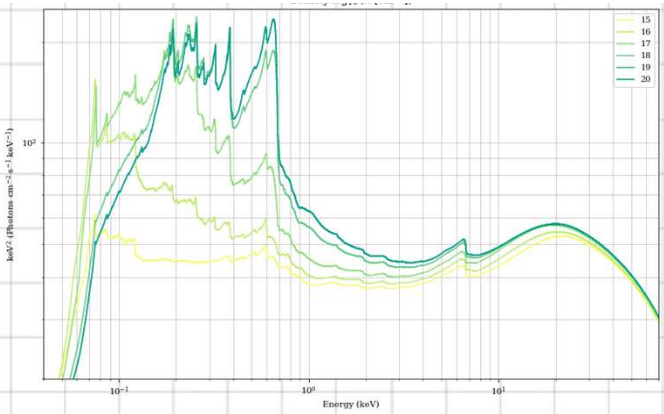
HEIGHT OF CORONA h



IONIZATION $\log_{10}(\xi)$

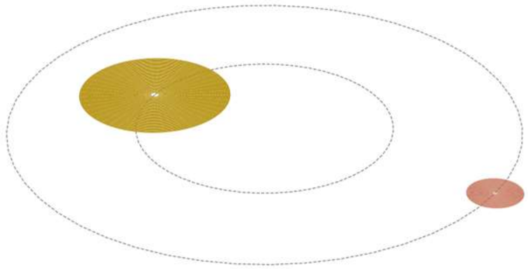


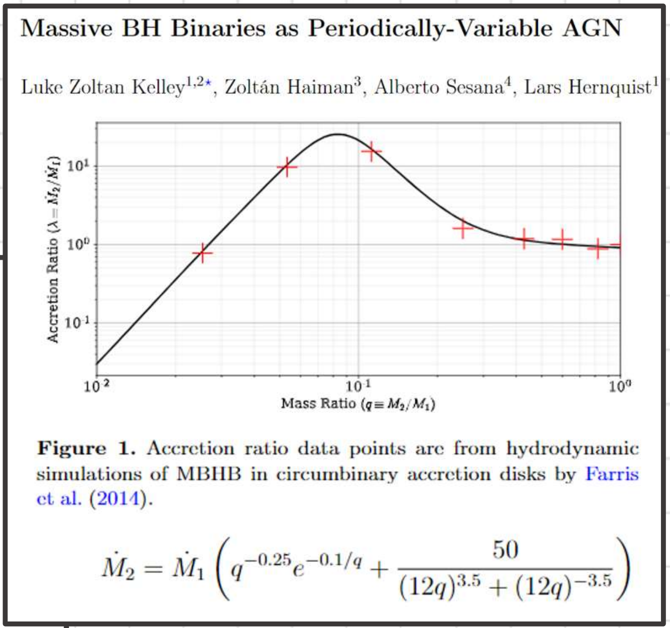
DENSITY $\log_{10}(n)$



P R E S C R I P T I O N S

- Relative mass accretion rates $f(q)$
- Ionization $\log \xi(\lambda,\ h,\ a)$
- Truncated minidisk $r_{out}(sep, e)$
- Normalization ∝ (disk area) x (mass accretion rate)
- Relativistic Doppler shift



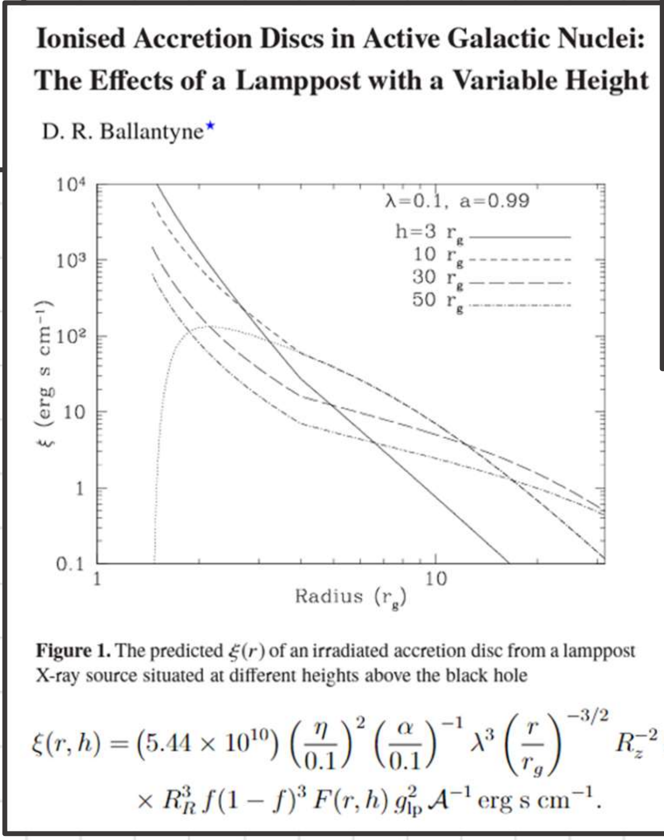


Massive BH Binaries as Periodically-Variable AGN

Luke Zoltan Kelley[1,2⋆], Zoltán Haiman[3], Alberto Sesana[4], Lars Hernquist[1]

Figure 1. Accretion ratio data points are from hydrodynamic simulations of MBHB in circumbinary accretion disks by Farris et al. (2014).

$$\dot{M}_2 = \dot{M}_1 \left(q^{-0.25} e^{-0.1/q} + \frac{50}{(12q)^{3.5} + (12q)^{-3.5}} \right)$$



Ionised Accretion Discs in Active Galactic Nuclei: The Effects of a Lamppost with a Variable Height

D. R. Ballantyne⋆

Figure 1. The predicted $\xi(r)$ of an irradiated accretion disc from a lamppost X-ray source situated at different heights above the black hole

$$\xi(r,h) = (5.44 \times 10^{10}) \left(\frac{\eta}{0.1}\right)^2 \left(\frac{\alpha}{0.1}\right)^{-1} \lambda^3 \left(\frac{r}{r_g}\right)^{-3/2} R_z^{-2} R_T^{-1} \times R_R^3 f(1-f)^3 F(r,h)\, g_{\rm lp}^2 \mathcal{A}^{-1} \text{ erg s cm}^{-1}.$$

PRESCRIPTIONS

- Relative mass accretion rates $f(q)$
- Ionization $\log \xi(\lambda,\ h,\ a)$
- Truncated minidisk $r_{out}(sep, e)$
- Normalization ∝ (disk area) x (mass accretion rate)
- Relativistic Doppler shift

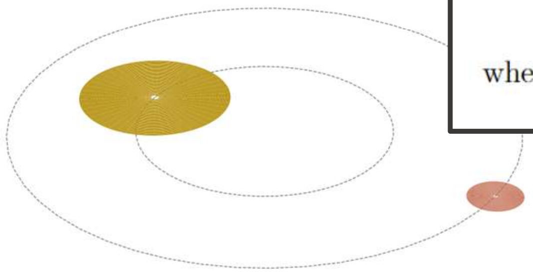
Normalization factor for relative luminosity

$$L_2 \simeq (\dot{m}_2/\dot{m}_1)\left(\frac{r_{\rm out,2}^2 - r_{\rm in,2}^2}{r_{\rm out,1}^2 - r_{\rm in,1}^2}\right) L_1$$

Orbital redshift (relativistic, circular)

$$(1+z)_i = \left(\frac{\omega}{\omega_{\rm obs}}\right)_i = \frac{\sqrt{1 - v_i^2/c^2}}{1 + v_i \sin f \sin i}$$

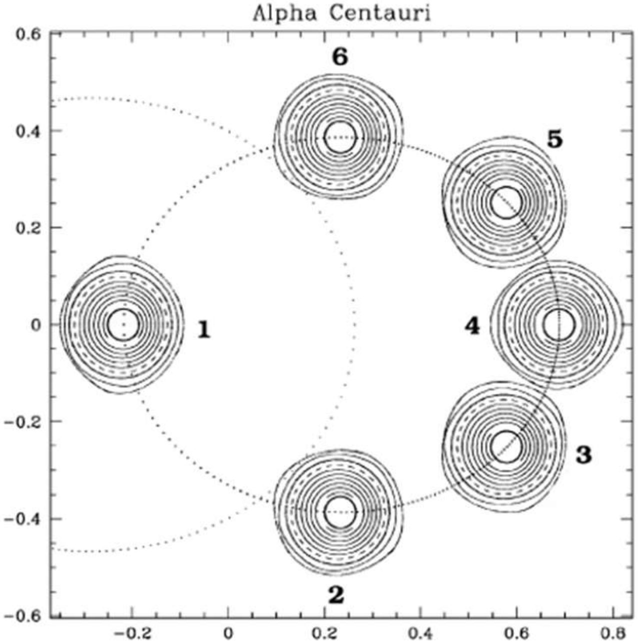
$$\text{where } v_1 = \frac{-qv}{1+q}, \quad v_2 = \frac{v}{1+q} \text{ and } v = \sqrt{\frac{GM}{\rm sep}}$$



Circumstellar and Circumbinary Disks in Eccentric Stellar Binaries

Barbara Pichardo[1,2★], Linda S. Sparke[1★], Luis A. Aguilar[3★]

$$r_{\rm out} \approx 0.733\,(1-e)^{1.20}\left(\frac{q}{1+q}\right)^{0.07} \cdot r_{\rm L}$$



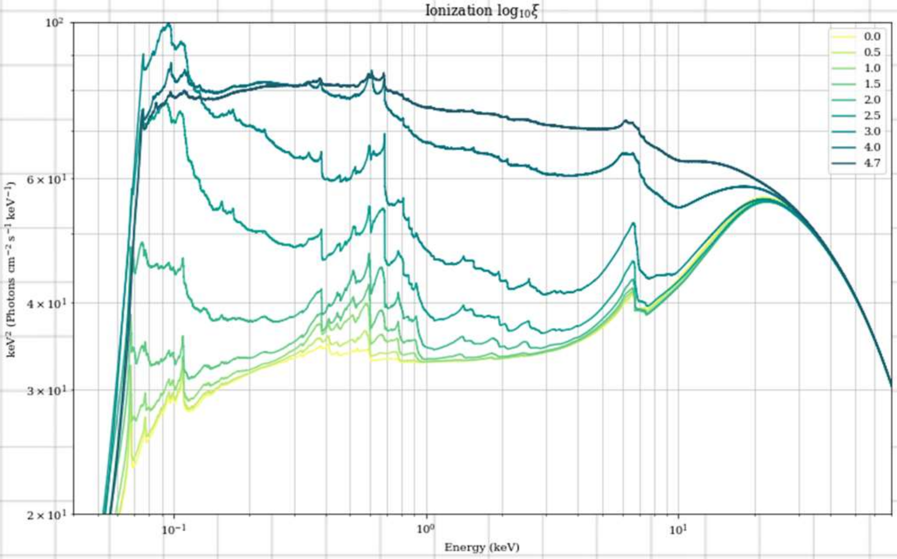
Truncation of circumbinary disks due to orbital motion, here modeled for Alpha Centauri at 6 different phases

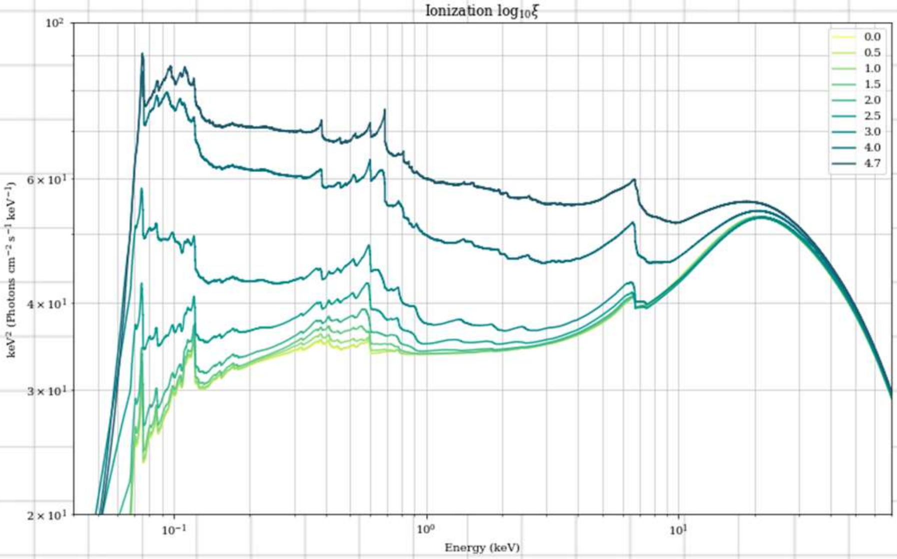
VARYING IONIZATION

NO SPIN $a = 0$

VS.

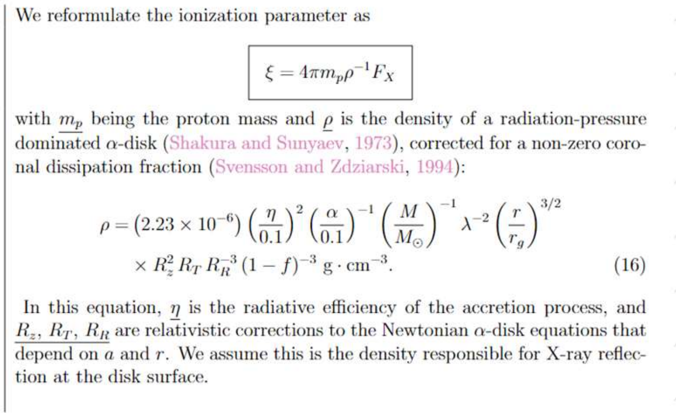
MAXIMALLY SPINNING $a = 0.99$





IONIZATION

ANALYTICAL FORMULA FOR $log\ \xi$ FOR ILLUMINATION BY A LAMPPOST CORONA



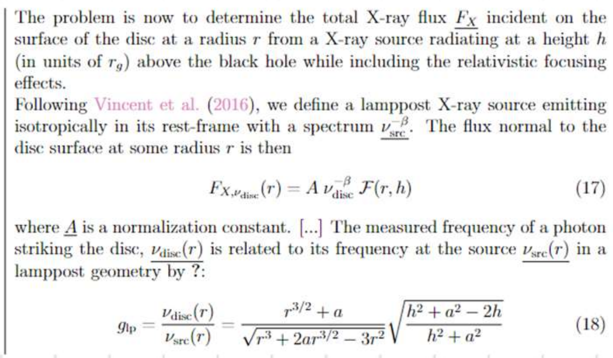
We reformulate the ionization parameter as

$$\boxed{\xi = 4\pi m_p \rho^{-1} F_X}$$

with m_p being the proton mass and ρ is the density of a radiation-pressure dominated α-disk (Shakura and Sunyaev, 1973), corrected for a non-zero coronal dissipation fraction (Svensson and Zdziarski, 1994):

$$\rho = (2.23 \times 10^{-6}) \left(\frac{\eta}{0.1}\right)^2 \left(\frac{\alpha}{0.1}\right)^{-1} \left(\frac{M}{M_\odot}\right)^{-1} \lambda^{-2} \left(\frac{r}{r_g}\right)^{3/2} \times R_z^2 R_T R_R^{-3} (1-f)^{-3}\ \mathrm{g \cdot cm^{-3}}. \quad (16)$$

In this equation, η is the radiative efficiency of the accretion process, and R_z, R_T, R_R are relativistic corrections to the Newtonian α-disk equations that depend on a and r. We assume this is the density responsible for X-ray reflection at the disk surface.

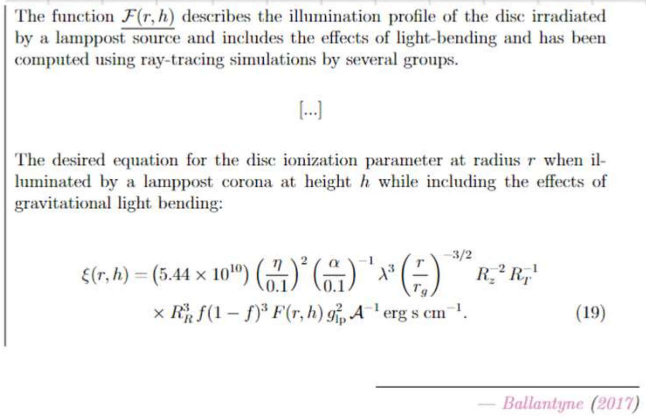


The problem is now to determine the total X-ray flux F_X incident on the surface of the disc at a radius r from a X-ray source radiating at a height h (in units of r_g) above the black hole while including the relativistic focusing effects.
Following Vincent et al. (2016), we define a lamppost X-ray source emitting isotropically in its rest-frame with a spectrum $\nu_{\mathrm{src}}^{-\beta}$. The flux normal to the disc surface at some radius r is then

$$F_{X,\nu_{\mathrm{disc}}}(r) = A\, \nu_{\mathrm{disc}}^{-\beta}\, \mathcal{F}(r,h) \quad (17)$$

where A is a normalization constant. [...] The measured frequency of a photon striking the disc, $\nu_{\mathrm{disc}}(r)$ is related to its frequency at the source $\nu_{\mathrm{src}}(r)$ in a lamppost geometry by ?:

$$g_{\mathrm{lp}} = \frac{\nu_{\mathrm{disc}}(r)}{\nu_{\mathrm{src}}(r)} = \frac{r^{3/2}+a}{\sqrt{r^3+2ar^{3/2}-3r^2}} \sqrt{\frac{h^2+a^2-2h}{h^2+a^2}} \quad (18)$$



The function $\mathcal{F}(r,h)$ describes the illumination profile of the disc irradiated by a lamppost source and includes the effects of light-bending and has been computed using ray-tracing simulations by several groups.

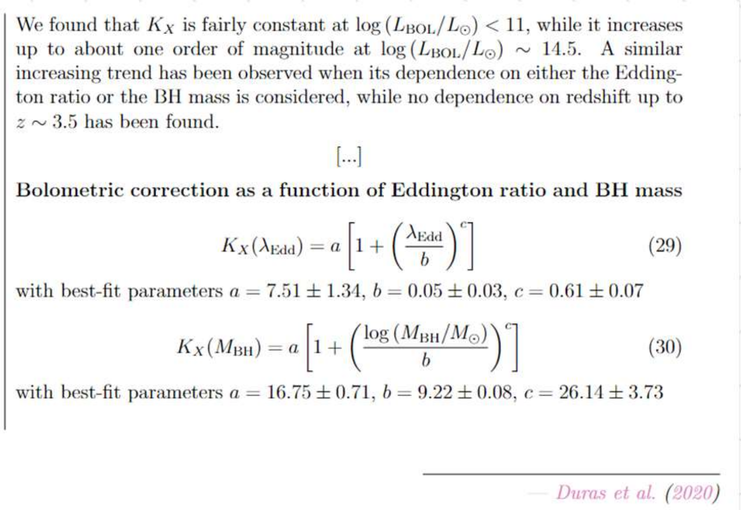
[...]

The desired equation for the disc ionization parameter at radius r when illuminated by a lamppost corona at height h while including the effects of gravitational light bending:

$$\xi(r,h) = (5.44 \times 10^{10}) \left(\frac{\eta}{0.1}\right)^2 \left(\frac{\alpha}{0.1}\right)^{-1} \lambda^3 \left(\frac{r}{r_g}\right)^{-3/2} R_z^{-2} R_T^{-1} \times R_R^3 f(1-f)^3 F(r,h)\, g_{\mathrm{lp}}^2 \mathcal{A}^{-1}\ \mathrm{erg\ s\ cm^{-1}}. \quad (19)$$

— Ballantyne (2017)

EMPIRICAL BOLOMETRIC CORRECTION FACTOR FOR X-RAY FLUX



We found that K_X is fairly constant at $\log(L_{\mathrm{BOL}}/L_\odot) < 11$, while it increases up to about one order of magnitude at $\log(L_{\mathrm{BOL}}/L_\odot) \sim 14.5$. A similar increasing trend has been observed when its dependence on either the Eddington ratio or the BH mass is considered, while no dependence on redshift up to $z \sim 3.5$ has been found.

[...]

Bolometric correction as a function of Eddington ratio and BH mass

$$K_X(\lambda_{\mathrm{Edd}}) = a\left[1 + \left(\frac{\lambda_{\mathrm{Edd}}}{b}\right)^c\right] \quad (29)$$

with best-fit parameters $a = 7.51 \pm 1.34$, $b = 0.05 \pm 0.03$, $c = 0.61 \pm 0.07$

$$K_X(M_{\mathrm{BH}}) = a\left[1 + \left(\frac{\log(M_{\mathrm{BH}}/M_\odot)}{b}\right)^c\right] \quad (30)$$

with best-fit parameters $a = 16.75 \pm 0.71$, $b = 9.22 \pm 0.08$, $c = 26.14 \pm 3.73$

— Duras et al. (2020)