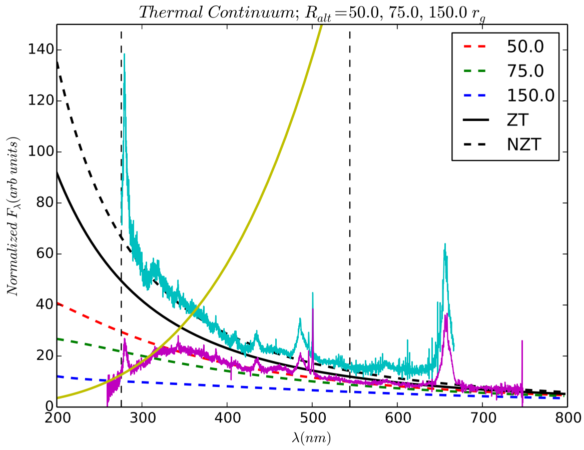

Figure 1: Plot of early 2000s spectrum (teal) and 2010 spectrum (purple) for contrast. Vertical dashed lines correspond to the span of observed V-band redshifted to rest frame. Teal spectrum is pretty well fit with a non-zero torque (NZT) boundary condition (black dashed line curve), ie puffed-up disk at ISCO. Solid black curve corresponds to a change in boundary condition from NZT to ZT (thin disk at ISCO). By contrast, the 2010 spectrum (purple) is well fit down to 350nm with a ZT model where the flux has been suppressed to 1% of normal. However, clearly at $\lambda < 350$nm we still need to kill some flux. Yellow green solid line shows a $F \propto \lambda^{-4}$ (rayleigh scattering) curve normalized to the flux at 350nm.

1 On the importance of also plotting on a linear scale

So, it looked on the log scale that we could nicely get a turnover in the MCD spectrum. However, if you fit the data that Dan sent around on a linear scale, as Saavik did (Fig.1) you can see that the suppression of flux from $R < 50r_g$ at 1% (dashed red line) gives you the right normalization for the 2010 spectrum but still misses the sharp cut-off. So we still need to preferentially kill off flux at higher wavelengths. Since our working model is some sort of disk cooling front propagating radially outwards, that made us think about the effect of scattering from increasing the density of scatterers (particularly Rayleigh scattering since this is $\propto \lambda^{-4}$) as the disk atmosphere collapses.

Now, have a look at the 2016 spectrum (Fig.2). It's the same as Fig. 1 except we've included the 2016 data (in that yellow-green colour). You can see that it looks like the 2010 curve down to 350nm, but the scattering screen has gone. Our hypothesis is that the atmosphere has fully collapsed by this point (the rain has ceased; this probably occurs on the freefall time in the disk).

Now since the optical depth to the mid-plane is $\tau = \kappa\Sigma/2$, where κ is the opacity and Σ is the disk surface density and the effective disk surface temperature $T_{\rm eff}$ can be written in terms of the midplane temperature $T_{\rm mid}$ as (Sirko & Goodman 2003; eqn. 4)

$$T_{\rm mid}^4 = \left(\frac{3}{8}\tau + \frac{1}{2}\right) T_{\rm eff}^4 \tag{1}$$

and since $\kappa = n_e\sigma_T + n_R\sigma_R$ where n_e is the electron density, n_R is the number density of Rayleigh scatterers, σ_T is the Thompson cross-section and σ_R is the Rayleigh cross-section ($\propto 1/\lambda^4$ where λ the incident wavelength). If $\tau \gg 1$ which we assume for an optically thick disk then, just thinking about the Rayleigh scatterers

$$T_{\rm eff} \approx \tau^{-1/4} T_{\rm mid} \propto n_R^{-1/4}\sigma_R^{-1/4} T_{\rm mid} \tag{2}$$

If we say that the disk cools and becomes thinner then the number density of scatterers (n_e, n_R) must increase. This increases κ and therefore τ, so the effective surface disk temperature drops (assuming the mid-plane is basically unchanged). If n_R increases by e.g. 10^4, then the effective surface temperature drops by an order of magnitude. The intensity of scattered radiation goes as $1/\lambda^4$. From Fig.2 in Sirko & Goodman (2003), you can see that the opacity can change by up to three orders of magnitude between the inner and outer disk.

2 Useful background for torques at the ISCO

From e.g. Zimmerman et al. (2005), we can write the maximum accretion disk temperature as

$$T_{\rm max} = f\left(\frac{3GM\dot{M}}{8\pi R_{in}^3\sigma}\right)^{1/4} \tag{3}$$

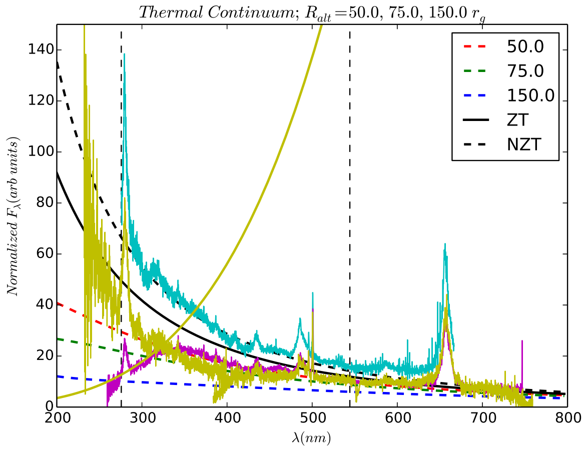

Figure 2: As Fig.1 except including 2016 spectrum now. Looks similar to 2010 except Rayleigh scattering no longer needed.

where M is the central mass, $\dot{M}$ is the accretion rate, R_{in} is the innermost radius of the disk and f is a parameter (O(1)) that approximates a spectral hardening modification from pure black body ($f = 1$). We can parameterize the innermost (maximum) disk temperature for a generic thin disk as

$$T_{\max} \approx 5.6 \times 10^5\text{K} \left(\frac{\mathrm{M_{BH}}}{10^8\mathrm{M}_\odot}\right)^{-1/4} \left(\frac{\dot{\mathrm{M}}}{\dot{\mathrm{M}}_{\mathrm{Edd}}}\right)^{1/4} \left(\frac{\eta}{0.1}\right)^{-1/4} \left(\frac{\mathrm{R_{in}}}{6\mathrm{r_g}}\right)^{-3/4} \left(\frac{\mathrm{f}}{2}\right) \quad (4)$$

where M_{BH} is the black hole mass, $\dot{M}$ is the accretion rate (in units of $\dot{M}_{\mathrm{Edd}}$), the Eddington accretion rate, $\eta \sim 0.1$ is the standard accretion efficiency, and $R_{in} = 6r_g$, the ISCO for a Schwarzschild BH. For comparison, keeping all the parameters the same but changing $M_{BH} = 10M_\odot$ yields $T_{\max} \sim 3.1 \times 10^7$K.

If the disk is thin, we expect there to be zero-torques at R_{in}, as the material plunges in free-fall at $r < R_{in}$. The resulting zero-torque temperature (T_{ZT}) profile is given by (Zimmermann et al. 2005)

$$T_{ZT} = T_{\max} \left(\frac{r}{R_{in}}\right)^{-3/4} \left[1 - \left(\frac{r}{R_{in}}\right)^{-1/2}\right]^{1/4} \quad (5)$$

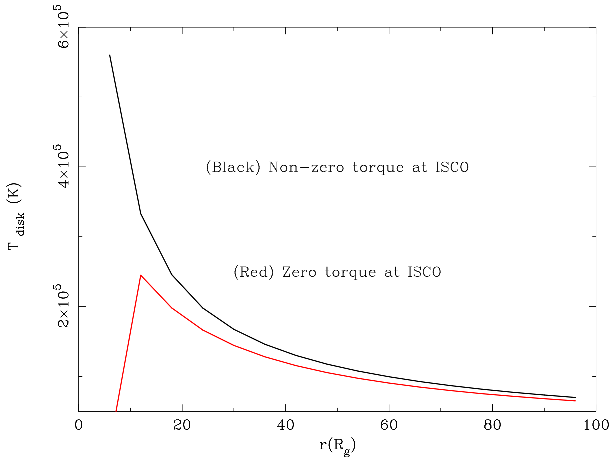

Figure 3: Comparison of the disk temperature profile using eqns.2-4, due to a change in the boundary condition at the inner edge (R_{in}). Red=standard zero torque at ISCO assumption. Black= non-zero torque at ISCO.

and is given by the red curve in Fig. 3. However, magnetic torques (Gammie 1999; Krolik & Agol 2000) or a puffed-up disk (Narayan et al. 1997; Ashfordi & Paczynski 2003) can have a finite or quite large torque at the inner edge. In this case, the disk temperature profile looks like

$$T_{NZT} = T_{\max} \left(\frac{r}{R_{in}} \right)^{-3/4} \tag{6}$$

or the black curve in Fig. 3.

Integrating over the temperature profiles above (Zimmermann et al. 2005) find

$$L_{\rm disk}[ZT, NZT] = [1,3] \frac{GM\dot{M}}{2R_{in}} \tag{7}$$

or the disk is $\times 3$ more luminous due to this extra torquing at R_{in}.

Fig. 4 shows the effect of changing $\dot{M}$ in eqn.(2). Black curve in Fig. 4 is the same as the black curve in Fig. 3, and the red and blue curves correspond to $\dot{M} = 0.1, 0.01\dot{M}_{\rm Edd}$ respectively.

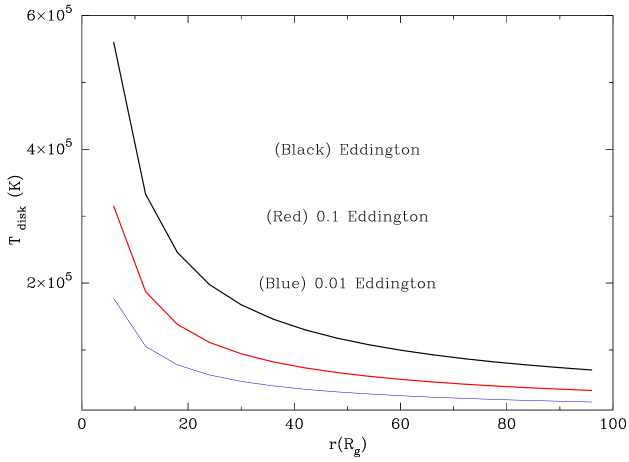

Figure 4: Comparison of the disk temperature profile using eqns.2-4, by changing the accretion rate. Black=1.0× Eddington. Red= 0.1×Eddington. Blue=0.01× Eddington.

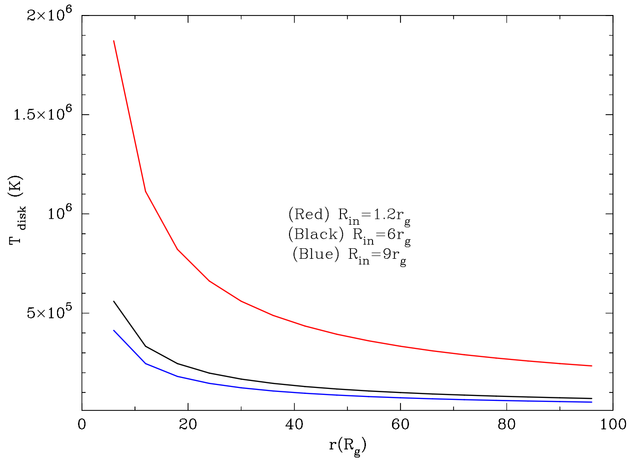

Figure 5: Comparison of the disk temperature profile using eqns.2-4, by changing the location of the disk inner edge (R_{in}). Red=$1.2r_g$ (max. spin Kerr BH, prograde compared to gas). Black=$6r_g$ (Schwarzschild BH, zero spin). Blue=$9r_g$ (max. spin Kerr BH, retrograde compared to gas).

Fig. 5 shows the effect of changing R_{in} in eqn.(2). Black curve in Fig. 5 is the same as the black curve in Fig. 3, and the red and blue curves correspond to $R_{in} = 1.2, 9.0r_g$ respectively.

Since from eqn. (5), $L_{\rm disk} = 3GM\dot{M}/2R_{in}$, going from $R_{in} = 6r_g \rightarrow 1.2r_g$ increases disk luminosity by a factor of $\times 5$ and keeping R_{in} fixed, but changing $\dot{M}$ by an order of magnitude changes $L_{\rm disk}$ by an order of magnitude.

3 What can we figure out from observations?

From Fig.1 in Nic's draft, we assume the source went from about 17.9mag to 18.5mag in the observed V-band over at most ∼100 days. This translates to a Johnson V-band flux density change from 0.262mJy to 0.151mJy. However, $1 + z = \lambda_{obs}/\lambda_{em} = 1.378$. So the observed V-band 380-750nm corresponds to 276-544nm in the rest frame (-6.56,-6.26 in log λ) or near UV to yellow in the quasar frame. Source flux density dropped to 58% of original in ~ 3 months. How does this compare with some of the modelling in the previous section?

Simply changing the boundary condition at R_{in} from non-zero torque to zero torque (e.g. collapsing a puffed-up disk inner edge, or, shudder, magnetic fields) leads to the difference between Fig. 6 and Fig. 7 as seen below. At $\log \lambda = -6.56$, the flux for $R_{in} = 9r_g$ (dark blue in both) drops by ~ 0.2 dex from ~ 38.0 to ~ 37.8 or from 10.0 to $6(\times 10^{37}$ ergs), or to 60% of the initial flux density, so consistent with the numbers above.

However, in the restframe spectrum in Nic's draft, the 300nm flux seems to drop by a factor of ~ 5 (how sure are we about this normalization?) It certainly seems like the flux at $\lambda < 350$nm is dropping relative to the optical flux 400-700nm. If the optical continuum were normalized to overlap, it looks like a factor of $2 - 3$ drop in relative flux at shorter wavelengths. In order to make the multi-color blackbody spectrum do this, we actually need dim large regions of the inner disk simultaneously.

For example, if the entire inner disk at $\leq 50r_g$ changed state and became dimmer on thermal timescales at each annulus, we can reproduce both the

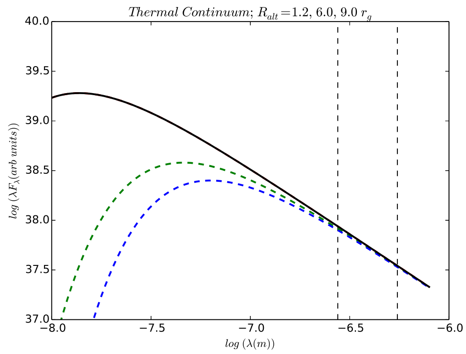

Figure 6: SED assuming a non-zero torque (puffed up disk/magnetic field) boundary condition at R_{in} and $\dot{M} = 0.01 M_{\rm Edd}$. Dashed lines are observed V-band converted to restframe wavelength. Red/Black=$1.2r_g$ (max. spin Kerr BH, prograde compared to gas). Green=$6r_g$ (Schwarzschild BH, zero spin). Blue=$9r_g$ (max. spin Kerr BH, retrograde compared to gas).

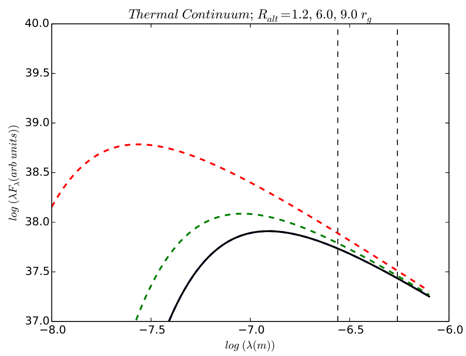

Figure 7: As previous figure, but for zero torque (thin disk) at ISCO.

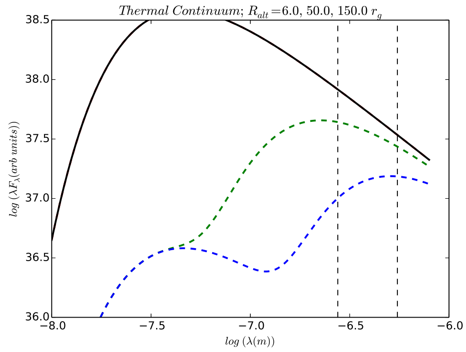

Figure 8: SED assuming a non-zero torque (puffed-up disk/mag. field) boundary condition at R_{in} and $\dot{M} = 0.01 M_{\rm Edd}$. Dashed lines are observed V-band converted to restframe wavelength. Black/Red=unperturbed disk down to $6r_g$. Green= dimming the disk by 1% at all radii $< 50r_g$. Blue= as green, but out to $150r_g$.

change at short λ and the observed V-band change . We can parameterize the relevant disk timescales at $R \sim 50r_g$ as:

$$t_{\rm orb} \sim 6{\rm days} \left(\frac{R}{50r_g}\right)^{3/2} \frac{r_g}{c} \tag{8}$$

$$t_{\rm th} \sim 6{\rm months} \left(\frac{\alpha}{0.03}\right)^{-1} \left(\frac{R}{50r_g}\right)^{3/2} \frac{r_g}{c} \tag{9}$$

$$t_{\rm front} \sim 11{\rm yr} \left(\frac{h/R}{0.05}\right)^{-1} \left(\frac{\alpha}{0.03}\right)^{-1} \left(\frac{R}{50r_g}\right)^{3/2} \frac{r_g}{c} \tag{10}$$

$$t_{\nu} \sim 230{\rm yr} \left(\frac{h/R}{0.05}\right)^{-2} \left(\frac{\alpha}{0.03}\right)^{-1} \left(\frac{R}{50r_g}\right)^{3/2} \frac{r_g}{c}. \tag{11}$$

The problem with this scenario is that you need thermal changes to occur simultaneously at each annulus in order to make this effect happen quickly. If this thermal change happens e.g. at small disk radii, you then need the effect to propagate on the $t_{\rm front}$ timescale. So, e.g. at $15r_g$, $t_{\rm front} \sim 2$yrs and at $50r_g$, $t_{\rm front} \sim 11$yrs, but at $150r_g$, $t_{\rm front} \sim 60$yrs.

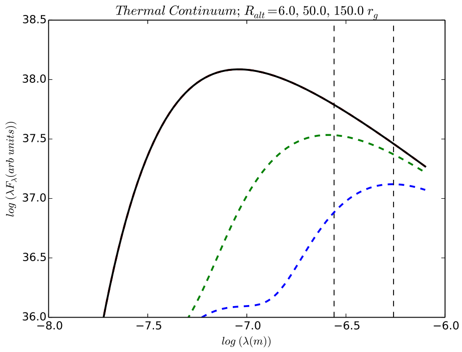

Figure 9: As previous Fig. but for zero-torque at ISCO (thin disk).

Figs. 8 and 9 show the effect of simultaneously dimming the flux to 1% of unperturbed disk from the innermost $< 50r_g$ (green), $< 150r_g$ (blue). We get the strong curvature in the continuum at short wavelength when we dim out to $\sim 150r_g$. We get some curvature when we dim out to $\sim 50r_g$.
Next steps: Maybe a change in R_{in} *and* NZT→ZT at the disk edge can explain both the 300nm drop by a factor of 2-3? I would lean towards the latter right now, as easier to explain (e.g. disk retreats a little and puffs up as local accretion rate drops temporarily). So stuff still to think about.

4 The heartbeat in GRS1915+105

Now if we look at the 'hearbeat' state in GRS 1915 + 105, we have $M_{bh} = 12.4^{+2}_{-1.8} M_\odot$ and $d = 8.6^{+2.0}_{-1.6}$kpc. The period of the oscillation is 50s. Translating this to a $M_{bh} = 10^8 M_\odot$, we get an equivalent light-crossing period of 50×10^7s or $\sim$ 16years. (Interesting: I wonder if e.g. PG 1302-105 is in a heartbeat state!?)

From Nielsen et al. 2011, their model (section 6 in their paper, Fig. 14, Table 3) for the heartbeat goes as:

1. a wave of excess material (from $\dot{M}$) originating between $20 - 30r_g$ and propagates radially inward and outward.

2. Disk responds by increasing R_{in} at constant temperature.
3. Disk luminosity increases quickly. At max. R_{in} drops sharply, temp. spikes, disk becomes unstable
4. Disk ejects material. Collides with corona. Hard X-ray pulse.
5. Disk relaxes, density wave subsides.
6. Intense X-ray wind from outer disk due to X-rays
7. Short lived jet

Relevant disk timescales around a $M_{bh} = 10^8 M_\odot$ at $R \sim 25 r_g$ are:

$$t_{\rm orb} \sim 2{\rm days}\left(\frac{R}{25r_g}\right)^{3/2}\frac{r_g}{c} \tag{12}$$

$$t_{\rm th} \sim 2.5{\rm months}\left(\frac{\alpha}{0.03}\right)^{-1}\left(\frac{R}{25r_g}\right)^{3/2}\frac{r_g}{c} \tag{13}$$

$$t_{\rm front} \sim 4{\rm yr}\left(\frac{h/R}{0.05}\right)^{-1}\left(\frac{\alpha}{0.03}\right)^{-1}\left(\frac{R}{25r_g}\right)^{3/2}\frac{r_g}{c} \tag{14}$$

$$t_{\nu} \sim 82{\rm yr}\left(\frac{h/R}{0.05}\right)^{-2}\left(\frac{\alpha}{0.03}\right)^{-1}\left(\frac{R}{25r_g}\right)^{3/2}\frac{r_g}{c}. \tag{15}$$

5 So is the heartbeat relevant?

From t_ν above, it seems like we'd need a slow rise (80-100years) for the first (long) part of the cycle. But that's not consistent with a $\sim$ 16yr period for the oscillation that you might expect from a simple scaling of light-crossing time ($10M_\odot \rightarrow 10^8 M_\odot$). At $10r_g$, t_ν above is 20yrs, so maybe. But why is the disk behaving like this at $10r_g$ (or $25r_g$ for that matter). Could predict observables based on the sequence above from Nielsen et al. (2011).
Nielsen et al. talk about a R_{in} getting closer to the BH accounting for the increase in $L_{\rm disk}$ but they don't explore a state-change as in Fig. 3. That should give us a different prediction and (shorter) timescales in general.

In general, we don't have a detailed oscillation profile and haven't seen it repeat, so can't really draw a parallel. Dead end for now, unless the cycle repeats.