The Radiative Efficiency of Accretion Flows in AGN

Shane Davis (IAS)
with Ari Laor

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Introduction

The radiative efficiency of QSOs can give us constraints on spin and/or other properties of the accretion flow near the black hole. Spin may be important for understanding jets, and it can tell us something about the accretion history of the black hole. Efficiency is also important for understanding the feedback of QSOs on their host galaxy environment.

Efficiencies of AGN can only be inferred via the Soltan argument (for the most part) which only gives an average efficiency for all QSOs collectively.

We propose and implement a method for estimating the efficiency of individual QSOs for which the bolometric luminosity and black hole mass can both be reasonably estimated. It assumes that optically emitting regions of QSOs are accretion powered and radiatively efficient i.e. that gravitational binding energy is radiated locally within the accretion disk.

Mass Estimates

We employ two types of mass estimates for sample of 80 PG QSOs: (1) BLR methods based on QSO broad emission lines and (2) the $M - \sigma$ relation from bulge stellar velocity dispersion measurements.

BLR mass estimates are computed assuming BLR velocity v_{blr} is given by FWHM of the Hβ line. The BLR radius is computed using the Kaspi et al. (2000) relation assuming $L_{46} = 8.3\ \nu L_\nu$ at 3000 ang.

$$M_{\rm blr} = R_{\rm blr} v_{\rm blr}^2 / G$$

$$R_{\rm blr} = 0.086 L_{46}^{1/2}$$

$M - \sigma$ estimates are computed using the Tremaine et al. (2002) relation with stellar velocity dispersions σ measured using H band CO absorption (Dasyra et al., 2007) or Ca H & K lines (Wolf and Sheinis, 2008).

$$M_\sigma = 1.35 \times 10^8 M_\odot \left(\frac{\sigma}{200\ {\rm km\ s^{-1}}} \right)^{4.02}$$

Radiatively Efficient Models

We assume a radiatively efficient accretion disk with constant accretion rate. Conservation of energy and angular momentum give flux as a function of radius:

$$F = \frac{3}{8\pi}\frac{G\dot{M}M}{R^3}Q(r, a_*, \ldots)$$

This form for the flux gives a characteristic scaling of the peak effective temperature of the hot inner disk:

$$T_{\rm eff,in} \propto \left(\frac{\dot{M}}{\dot{M}_{\rm Edd}}\right)^{1/4}\left(\frac{M}{M_{\rm Sun}}\right)^{-1/4}$$

Spectrum is obtained by integrating over radius and assuming blackbody emission:

$$\nu L_\nu \propto \cos i \; \nu^{4/3}\dot{M}^{2/3}M^{2/3}\Theta(\nu, r_{,\rm in}, \ldots)$$

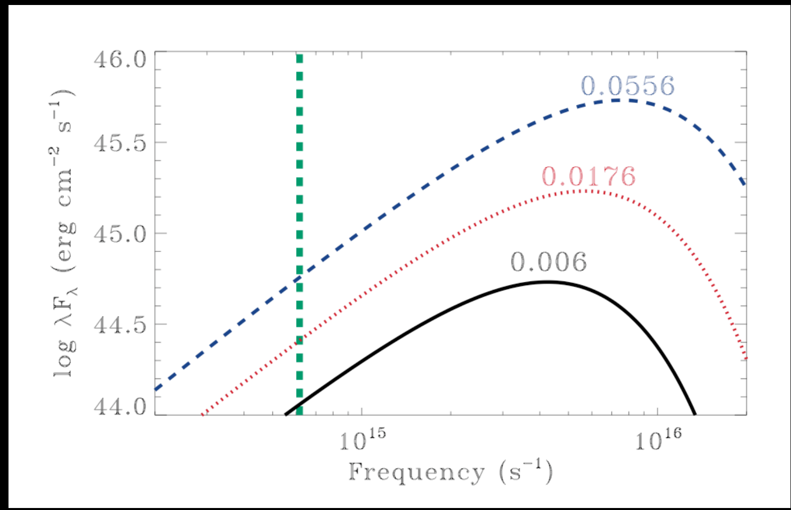
with Θ nearly constant. Given νL_ν for a particular ν and M we can invert this to find accretion rate. Efficiency η is then given by:

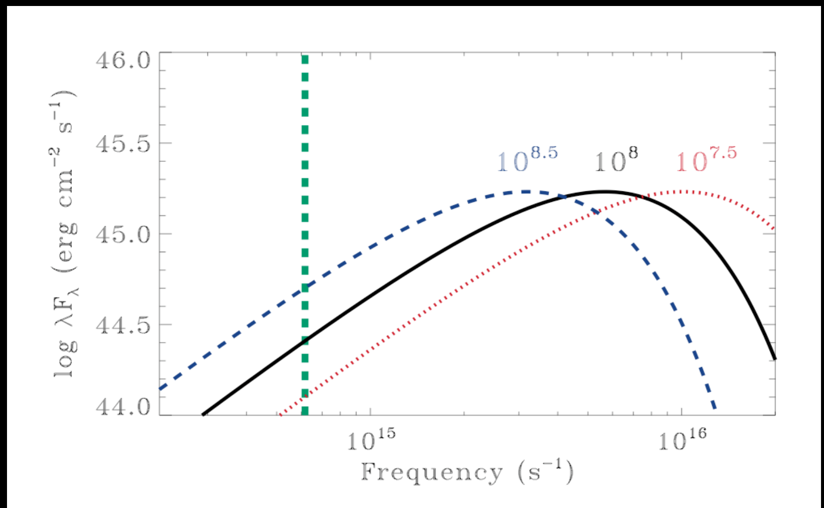
$$\eta = \frac{L_{\rm bol}}{\cos i \dot{M} c^2}$$

For our work, we use more sophisticated models which include relativistic effects and (in some cases) realistic atmosphere models instead of blackbodies (Agol 1997; Hubeny et al. 2000). These give slightly different results but mass and accretion rate scalings are the same as above.

Mass, Accretion Rate, and Optical Luminosity

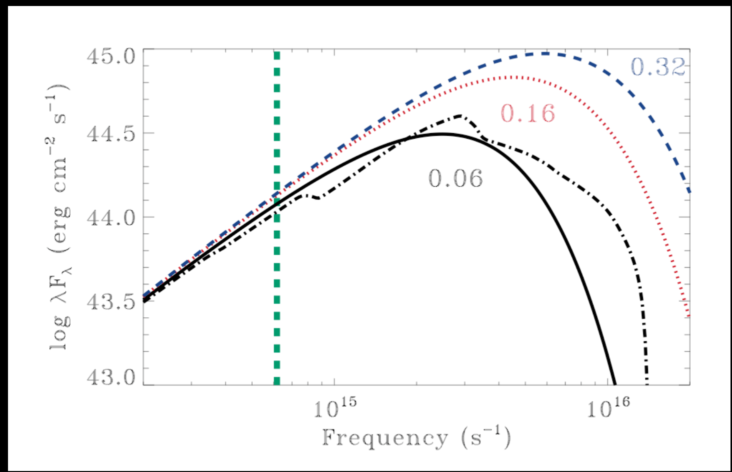
Fixed efficiency, fixed mass and varying accretion rate => L_{opt} varies





Fixed efficiency, fixed accretion rate and varying mass => L_{opt} varies

Comparison of Derived Accretion Rates

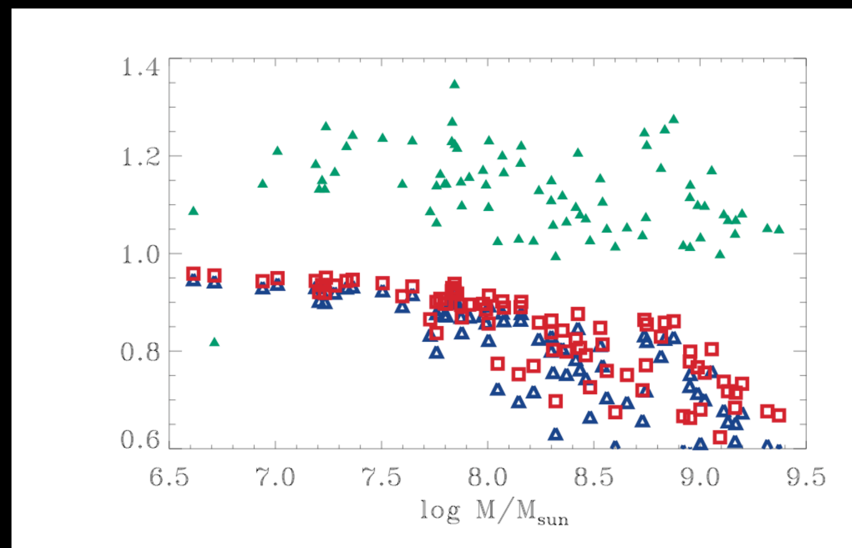


Fixed mass, fixed accretion rate and varying efficiency (spin) => L_{opt} is approximately constant

L_{opt} & M (almost) uniquely determine accretion rate:

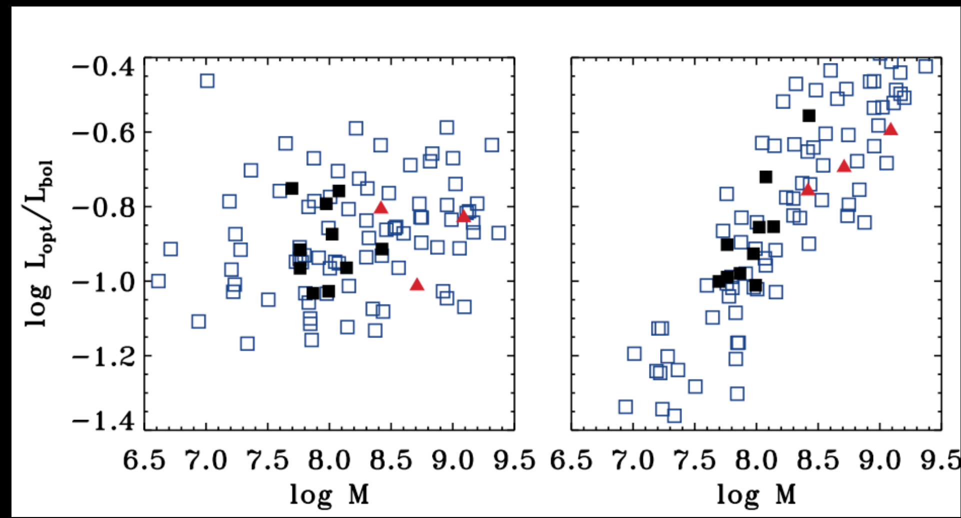
$$\dot{M} = 3M_\odot\ \mathrm{yr}^{-1}\left(\frac{L_{opt}}{10^{45}\mathrm{erg\ s^{-1}}}\right)^{3/2}\left(\frac{M}{10^8 M_\odot}\right)^{-1}$$

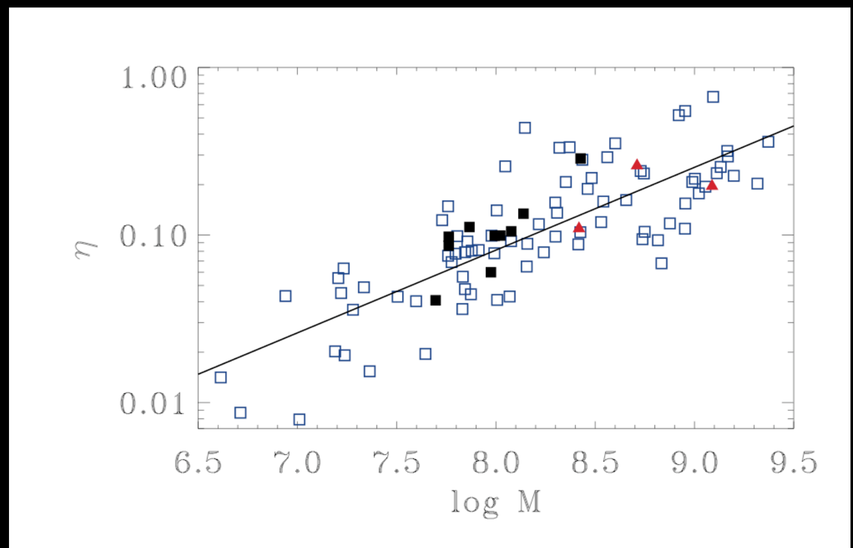
We fit for accretion rate in 80 PG QSOs by matching L_{opt}, assuming $M_{BH} = M_{blr}$ and $\cos i$ = 0.75. The plot on right compares the ratios of accretion rates derived using four different spectral models: $a_* = 0$ (blackbodies and atmospheres), $a_* = 0.9$, and $a_* = 0.998$.



PG QSOs and Derived Efficiencies

L_{opt}: νL_ν at 4681 ang
L_{bol}: estimated using optical, UV and X-ray data (non contemporaneous)
M: BLR estimates (blue open squares), M - σ with Dasyra et al. (black filled squares) and with Wolf & Sheinis (red filled triangles)

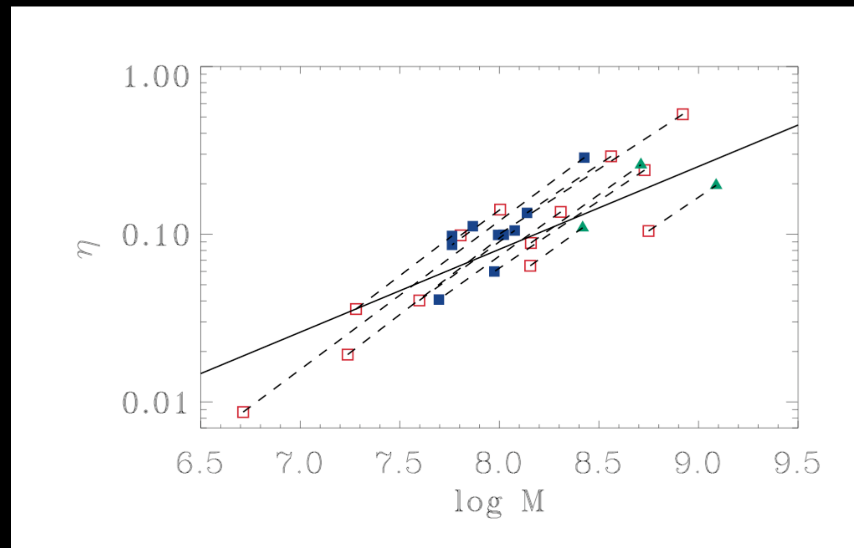




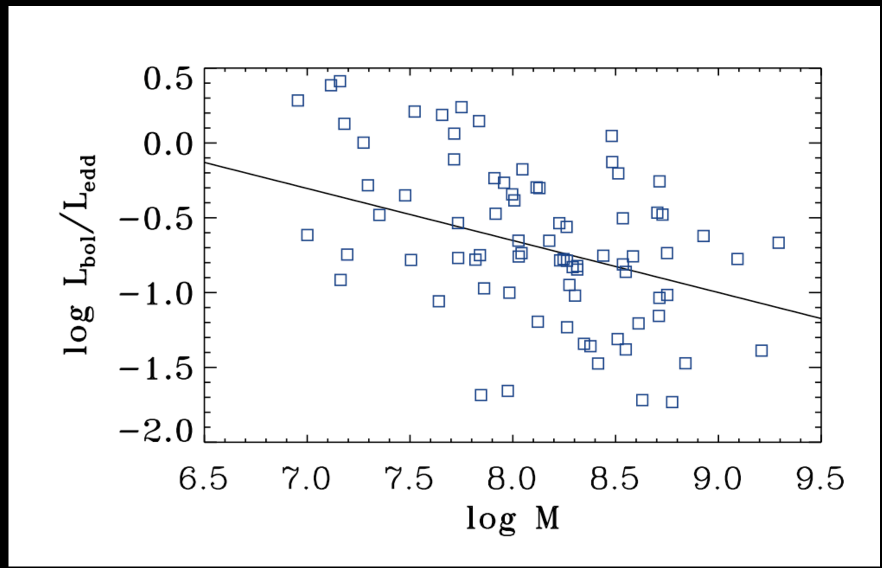
Efficiency η derived by fitting optical luminosity with $a_* = 0.9$ blackbody model and assuming $\cos i = 0.75$ using L_{bol} and M estimates.

How Reliable are BLR Masses?

Efficiencies are strongly dependent on reliability of mass estimates. Plot compares efficiencies derived using $M - \sigma$ to those using M_{blr} for those sources where both are available.

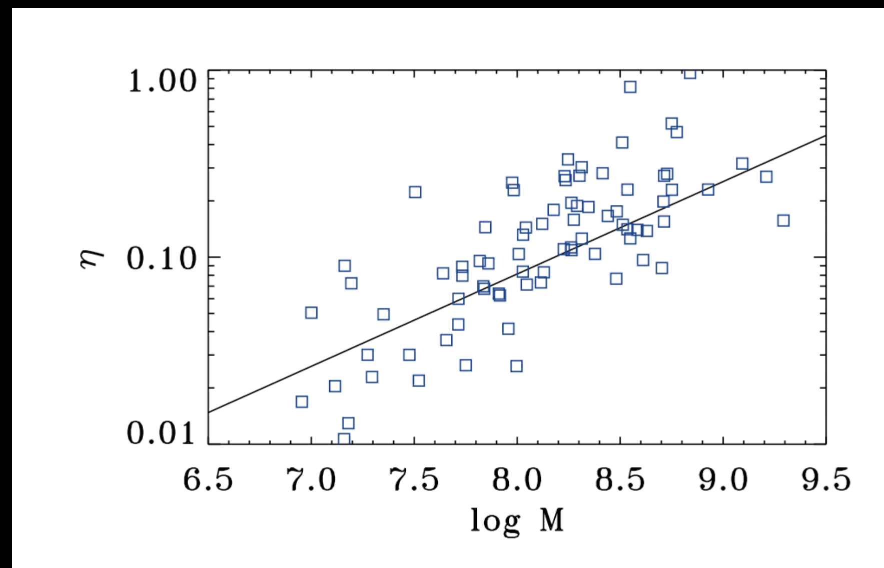


Monte Carlo Distributions

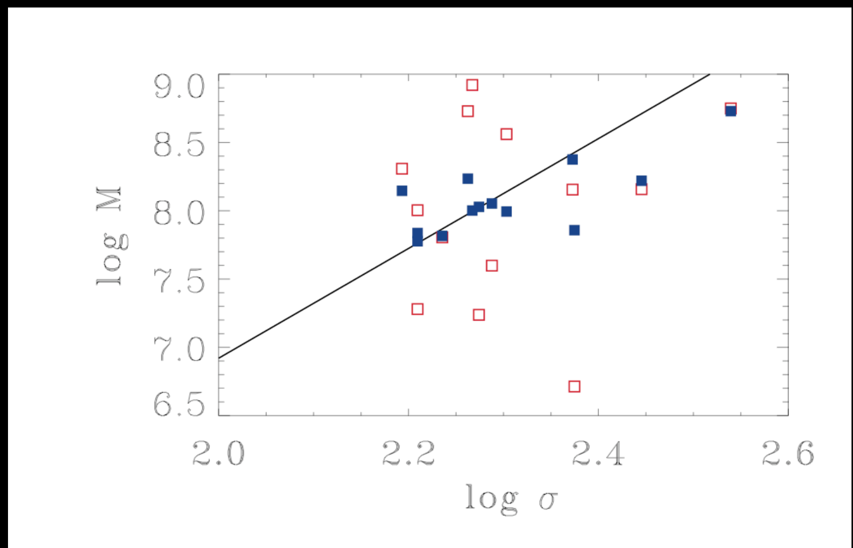


We can test mass uncertainty hypothesis via MC realizations: Assume log-normal distributions in M and L/L_{edd}. The σ for the intrinsic distribution is 0.4 dex, but we assume log-normal error of 0.5 dex for mass estimate.

Low masses are underestimates so efficiency is underestimated. High masses are overestimates so efficiency is overestimated. Intrinsic efficiency of all model spectra is 10%.



Efficiency Based Mass Estimates

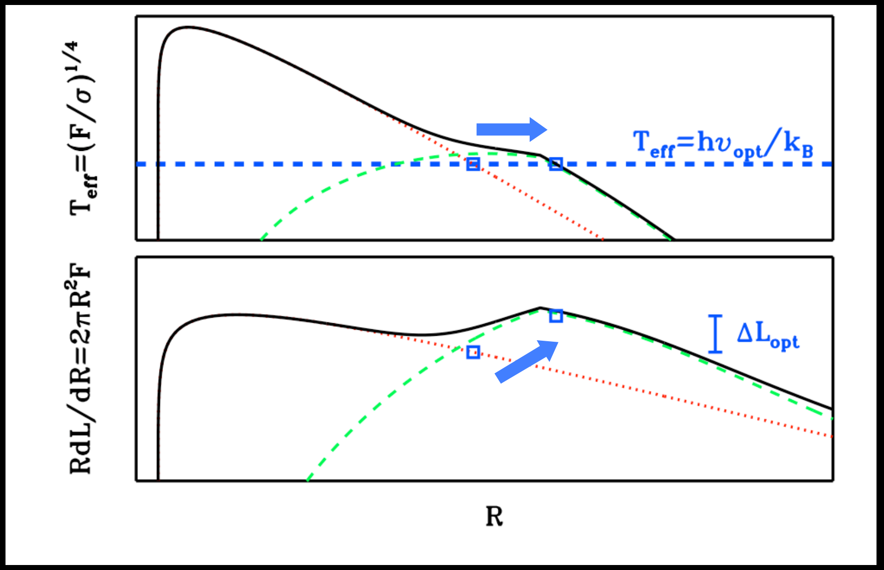


Can invert procedure to get mass, assuming single value for efficiency ($\eta = 0.1$) and inclination. Every single mass lies closer to the M - σ relation than its M_{blr} counterpart.

Is the Radiatively Efficient Model Incorrect?

We have neglected irradiation which must be present at some level. (Although amplitudes of correlated Optical -- UV variablity are small.)

However, irradiation *always* enhances L_{opt} above the "intrinsic" optical emission of the unirradiated disk. This mean that accretion rates has been overestimated and the efficiencies have been underestimated.



Other possibilities include mass loss to a wind, energy loss to a corona or due to advection. None of these obviously gives a weaker dependence of L_{opt}/L_{bol} on mass, and would require some level of fine tuning.

Conclusions

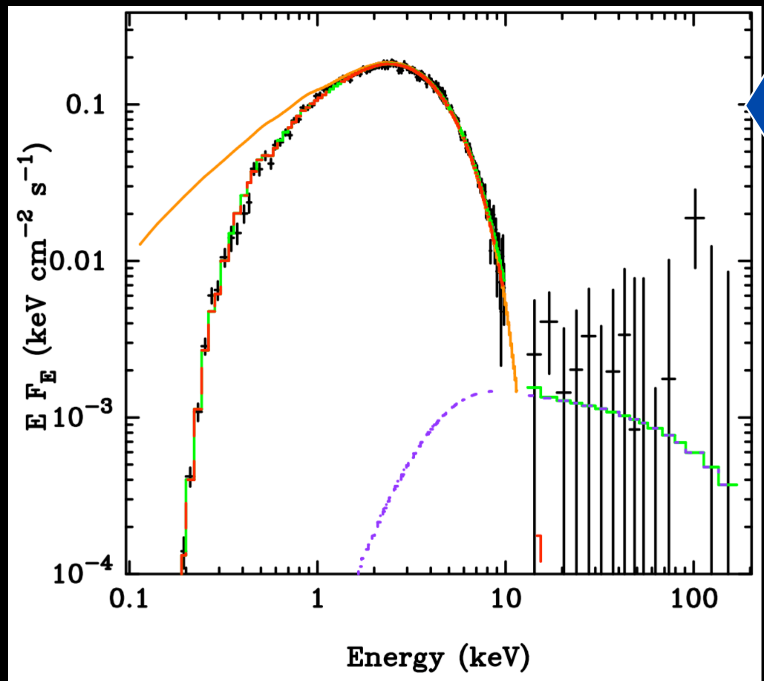
I. In a standard accretion disk model, accretion rate is uniquely determined by L_{opt}, i, and M. Accretion rate and L_{bol} then determine the efficiency.

II. The observed range of L_{opt}/L_{bol} is much narrow than expected, given the range of masses that are inferred. This leads to a correlation of M and η when using the above method. Such a correlation is not easily understood from theory.

III. One possibility is that mass range is narrower than M_{blr} suggests. This seems implausible, but would be consistent with $\sim 10\%$ efficiency if true.

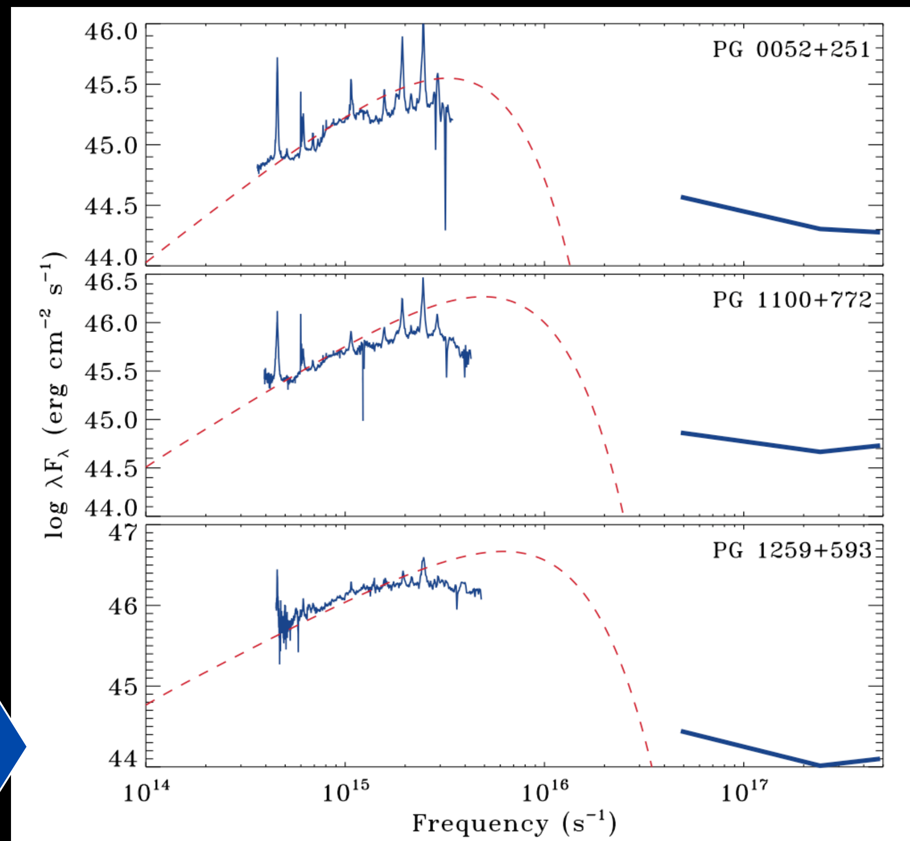
IV. Alternatively, the radiatively efficient assumption may be wrong. One possibility is irradiation, but this would further increase the effciency, which is already uncomfortably large at high mass end.

Do AGN look like Accretion Disks?



SWD, Done, & Blaes 2006

High/Soft state X-ray binaries are well modeled by multi-temperature blackbody accretion disks.



Optical/Hubble/Fuse spectra -- Brotherton et al.

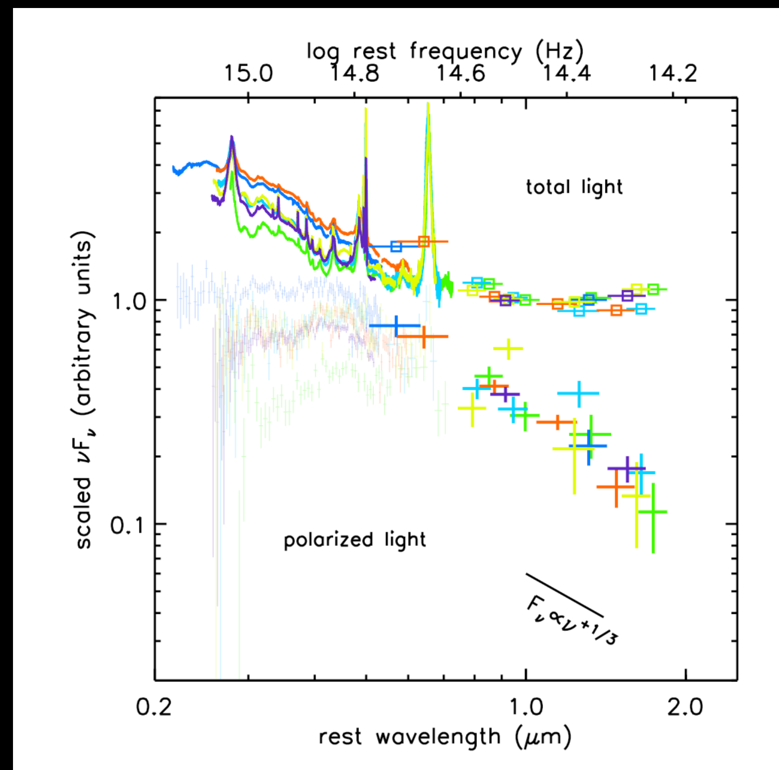
AGN are *not* simple accretion disks: spectra are too flat in the UV and have significant X-ray emission.

Are Radiatively Efficient Disks a Viable Model?

Microlensing variability in gravitationally lensed quasars gives some independent constraints on the location of the emitting region as a function of frequency. There are disagreements, but there are claims that emission region is too large to be a radiatively efficient accretion disk.

Polarized flux can be used to probe the intrinsic emission with dust removed. Some sources show evidence for the expected $\nu F_\nu \sim \nu^{4/3}$ profile optical to infrared.

Optical spectral slopes (4000 - 5100 ang) of SDSS QSOs are well fit by radiatively efficient disk models (Hubeny et al. 2000; Bonning et al. 2007).



Kishimoto et al. 2008