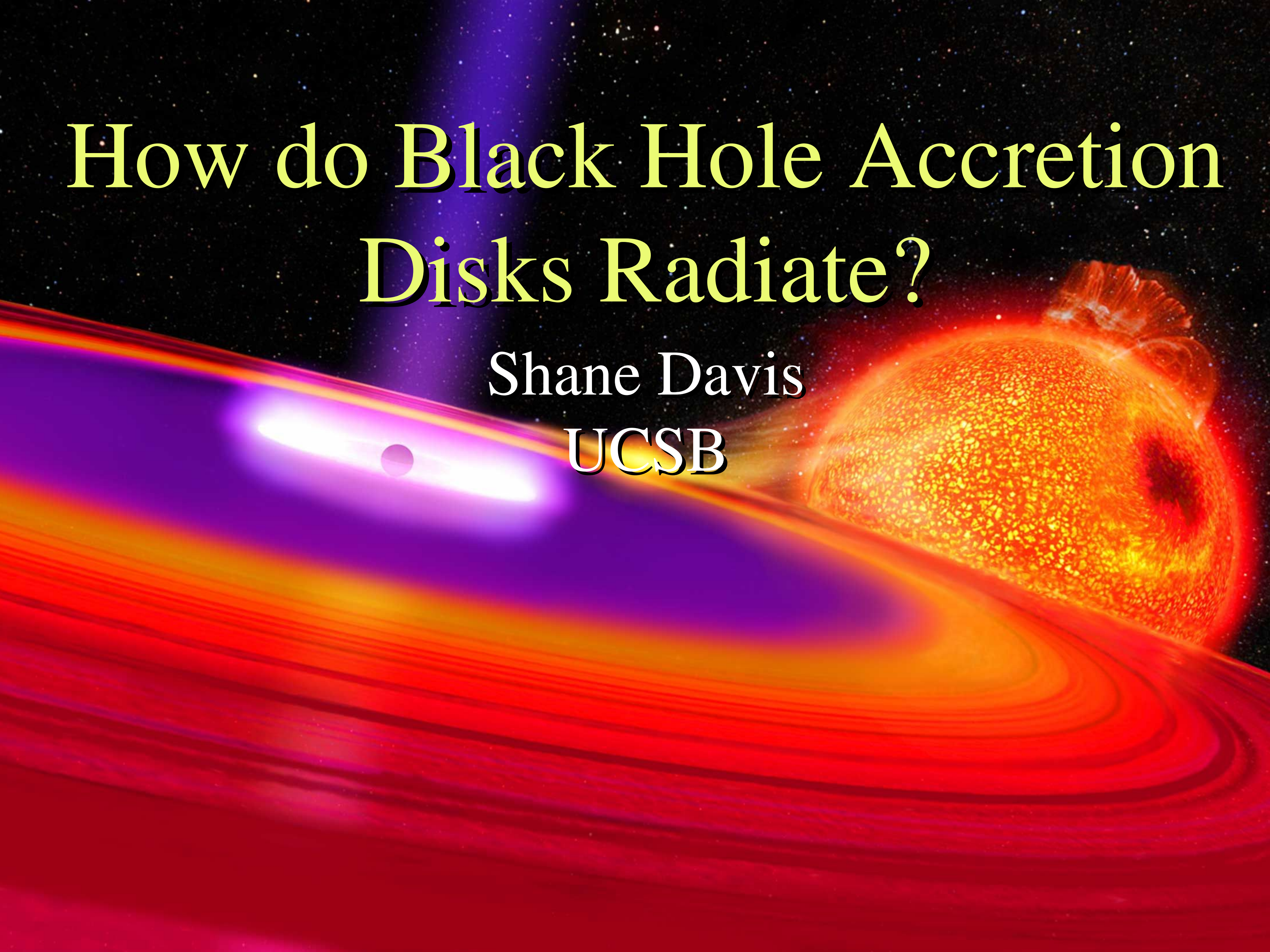
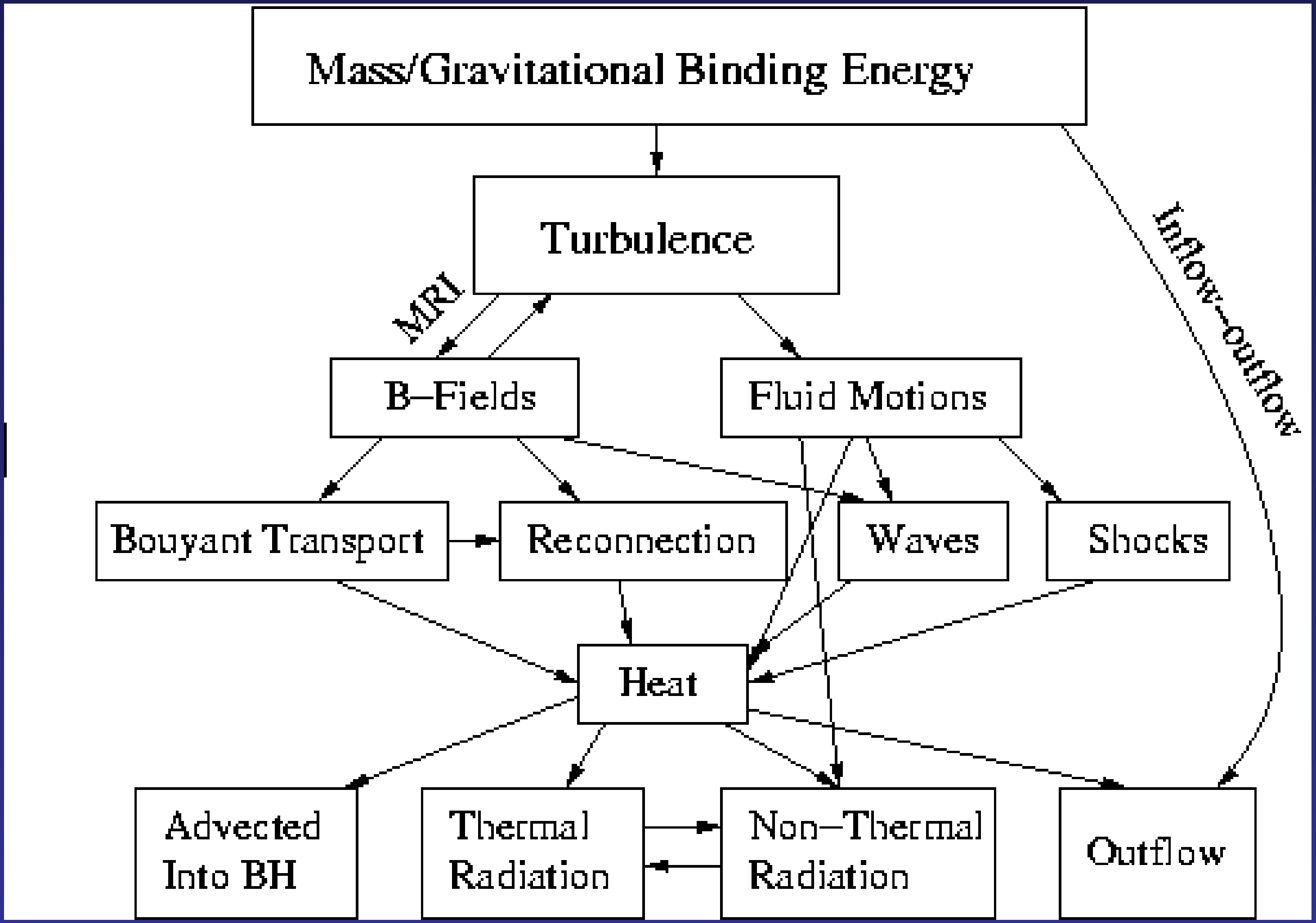


How do Black Hole Accretion Disks Radiate?

Shane Davis
UCSB

Standard Accretion Picture



Issues Addressed in This Talk

- How does the release of gravitational binding energy lead to ~ thermal radiation?
- Are thin disk (α-disk) models sufficient to explain observations? (yes and no)
- How do lifting the simple assumptions of the α-disk model alter the spectra?

I: Summary of Models and Observations

The thin disk model

- H/R << 1
- Constant accretion rate; time-steady
- Gravitational binding energy released locally as radiation:

$$F \simeq -H\tau_{R\phi}R\frac{\partial\Omega}{\partial R}$$
$$\dot{M}\frac{\partial R^2\Omega}{\partial R} = \frac{\partial}{\partial R}(4\pi R^2 H\tau_{R\phi})$$

The α-disk model

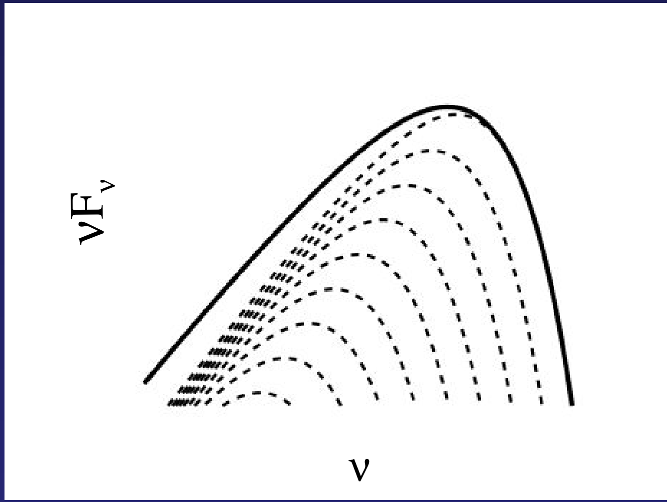
- $\tau_{R\phi} = \alpha P$ determines surface density Σ
- Vertical dissipation distribution:

$$\frac{dF}{dz} = \frac{2\sigma T_{\rm eff}^4}{\Sigma}\rho$$

The Multicolor Disk Model (MCD)

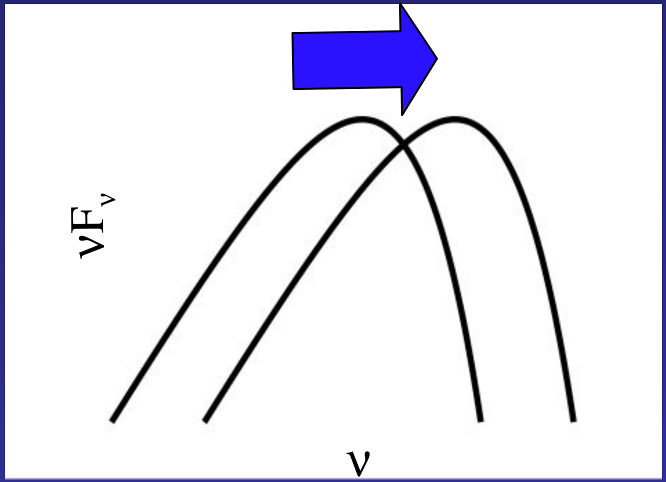
- Consider simple temperature distribution:

$$T_{\text{eff}} \propto R^{-3/4}$$



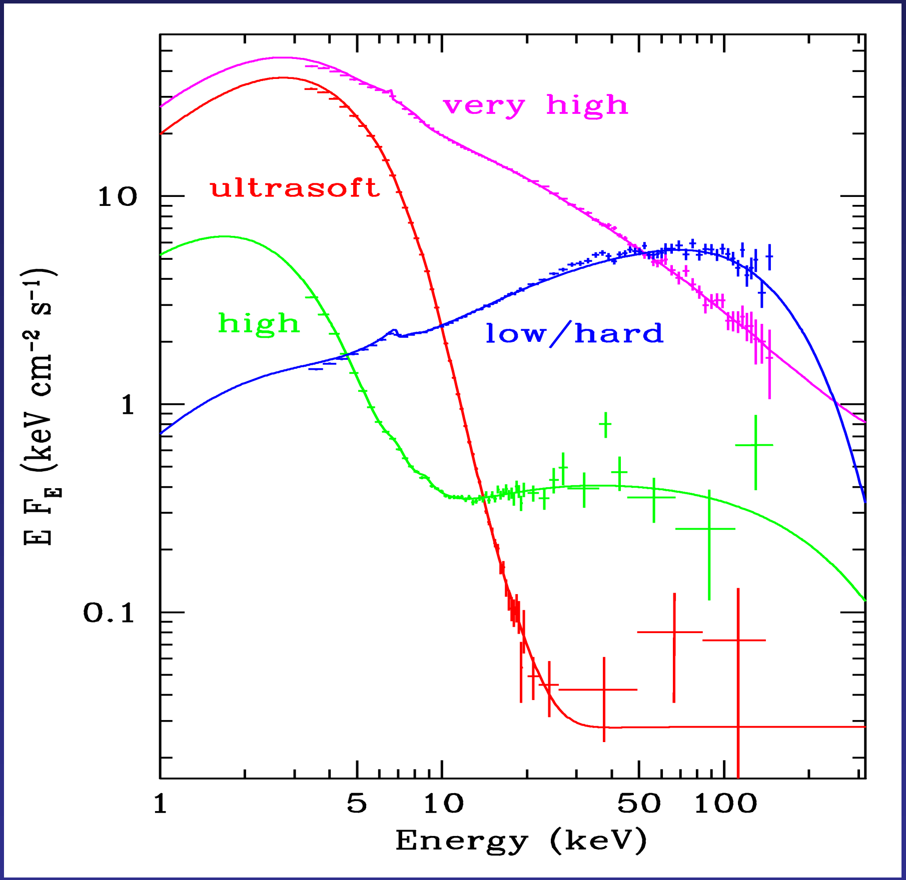
- Spectrum assumed to be color-corrected blackbody:

$$I_\nu = f_{\text{col}}^{-4} B_\nu(f_{\text{col}} T_{\text{eff}})$$



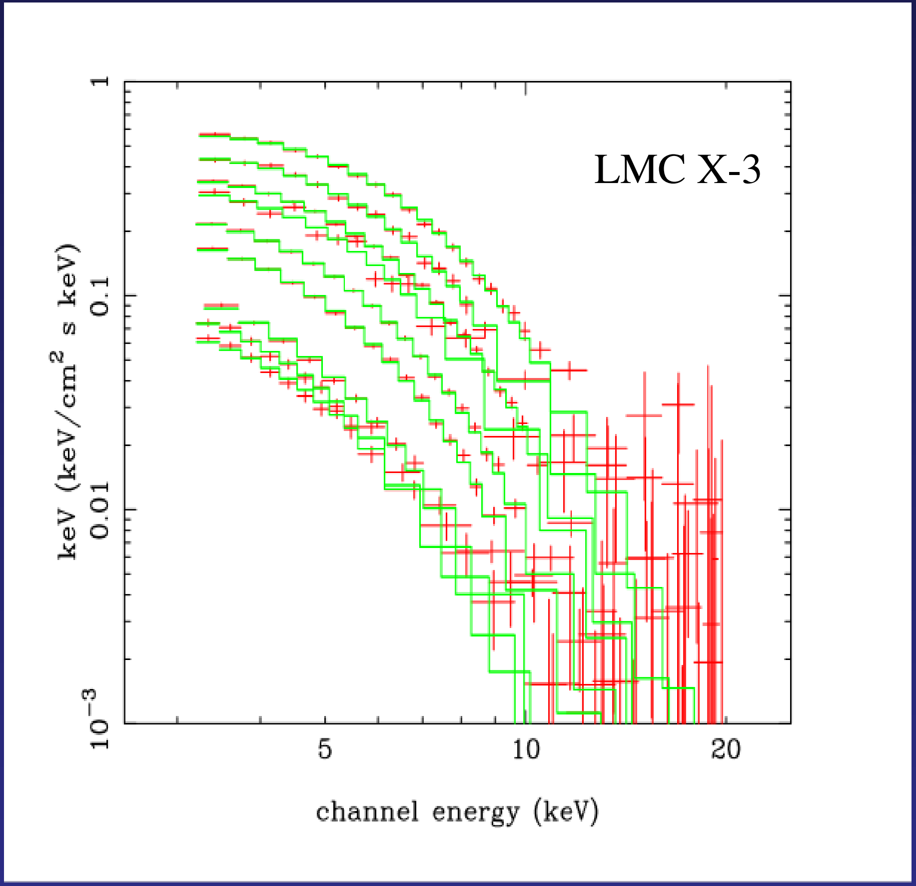
Spectral States of BHBs

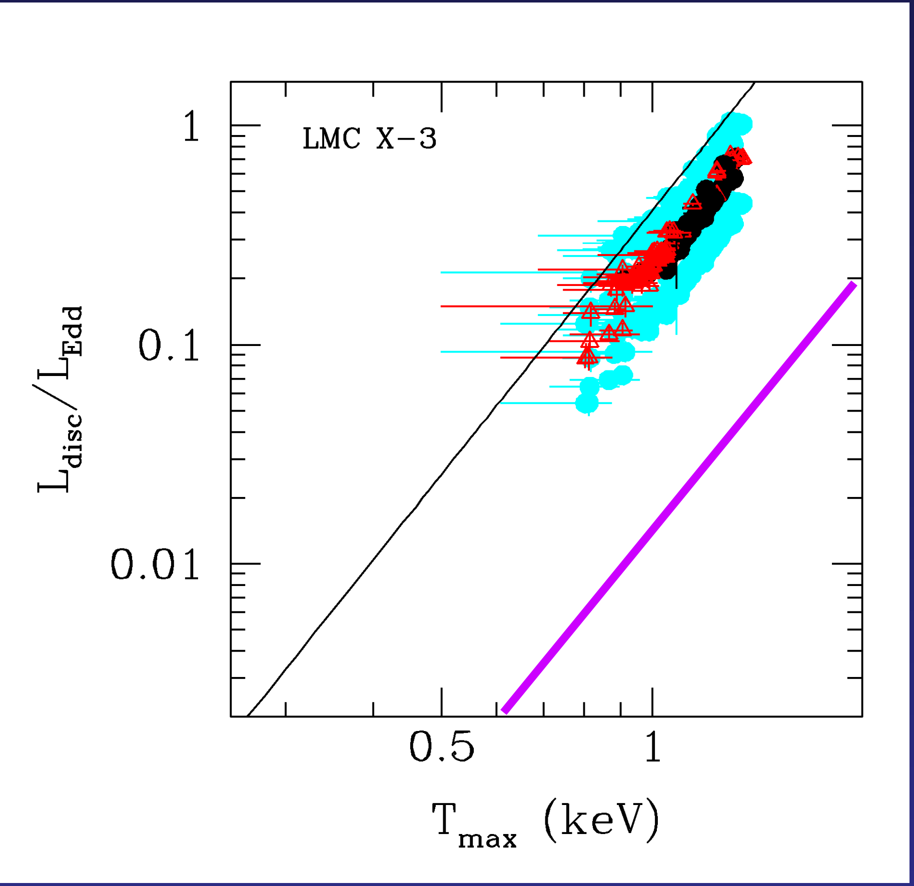
- Spectral states specified by relative contributions of thermal (disk) and non-thermal emission (corona)
- High/Soft state is dominated by thermal disk-like component



Done & Gierlinski 2004

Disk Dominated Spectra



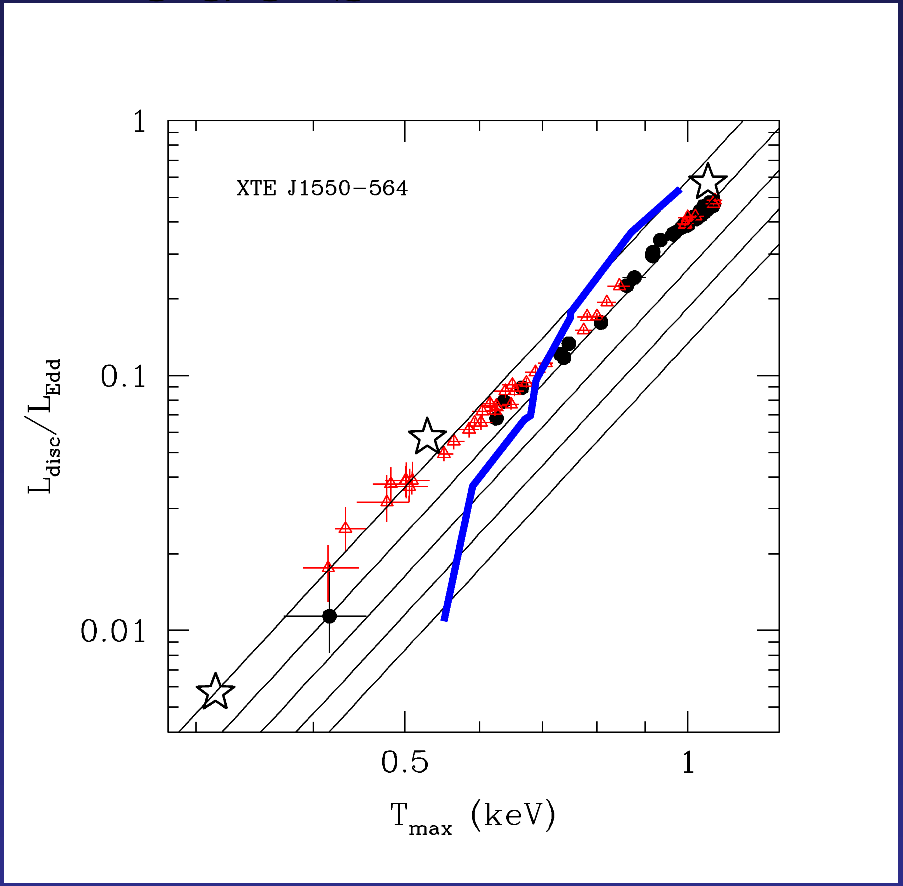


Gierlinski & Done 2004

- L prop. to T^4 suggests f_{col} and emitting area are constant

Comparison with Previous Spectral Models

- Previous α-disk models provide mixed results
- Shimura & Takahara (1995); full atmosphere calculation, free-free emission and Compton scattering: stars
- Merloni, Fabian & Ross (2000); relativistic effects, constant density, f-f emission and Compton scattering: blue curve
- Small scatter in L-T relation as L varies by over an order of magnitude



Gierlinski & Done 2004

How do we Improve on these Models

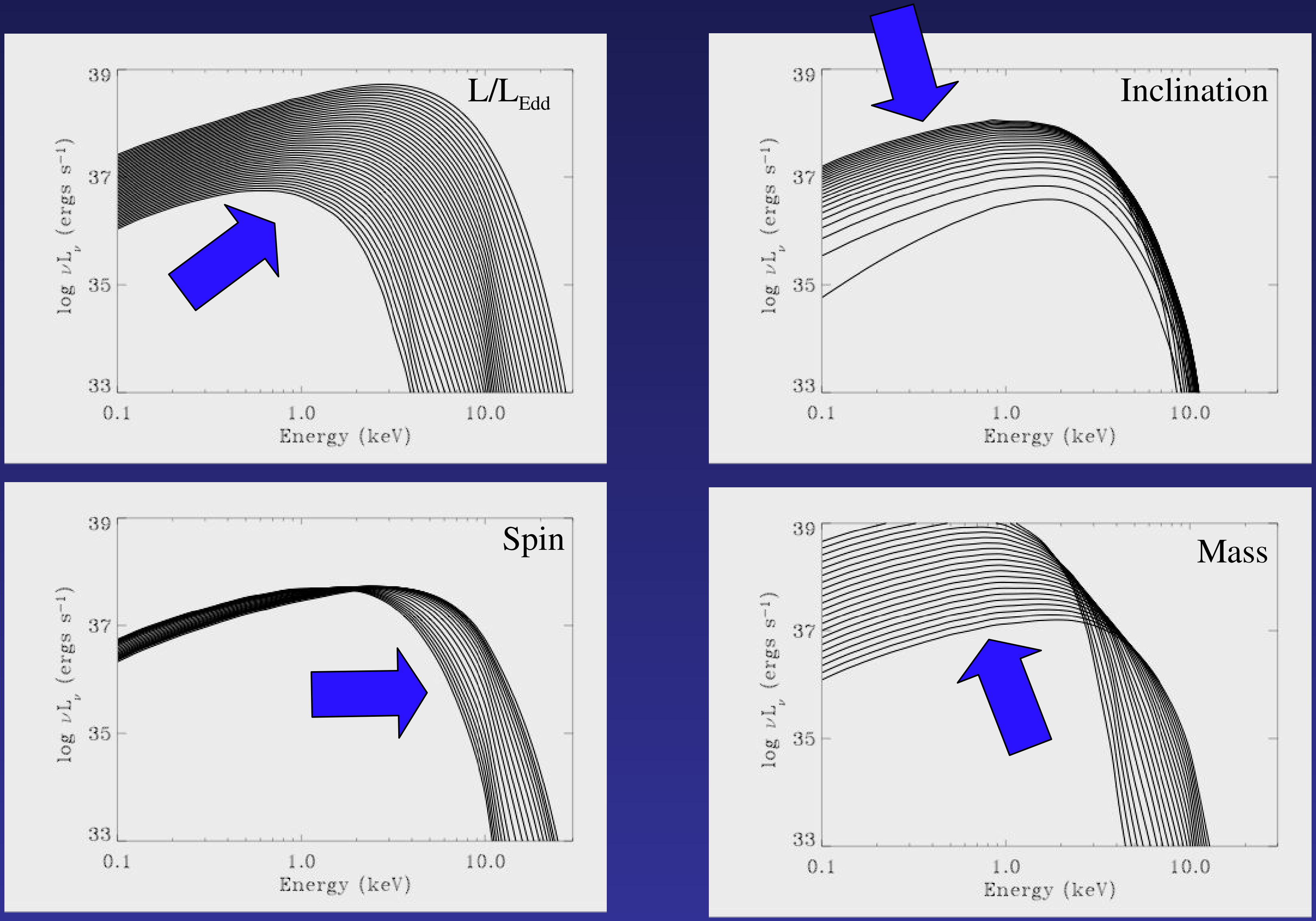
- Include metals; non-LTE populations
- Improved radiative transfer and better treatment of Compton Scattering
- Examine the effects of:

  dissipation, magnetic stresses, and inhomogeneities

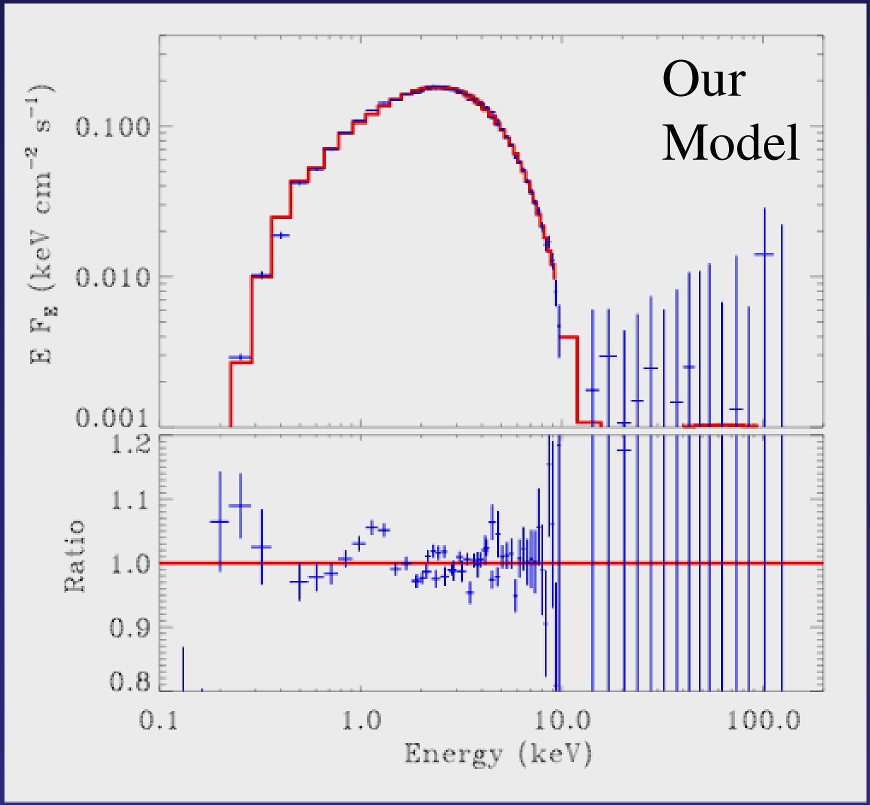
Our Models, Briefly

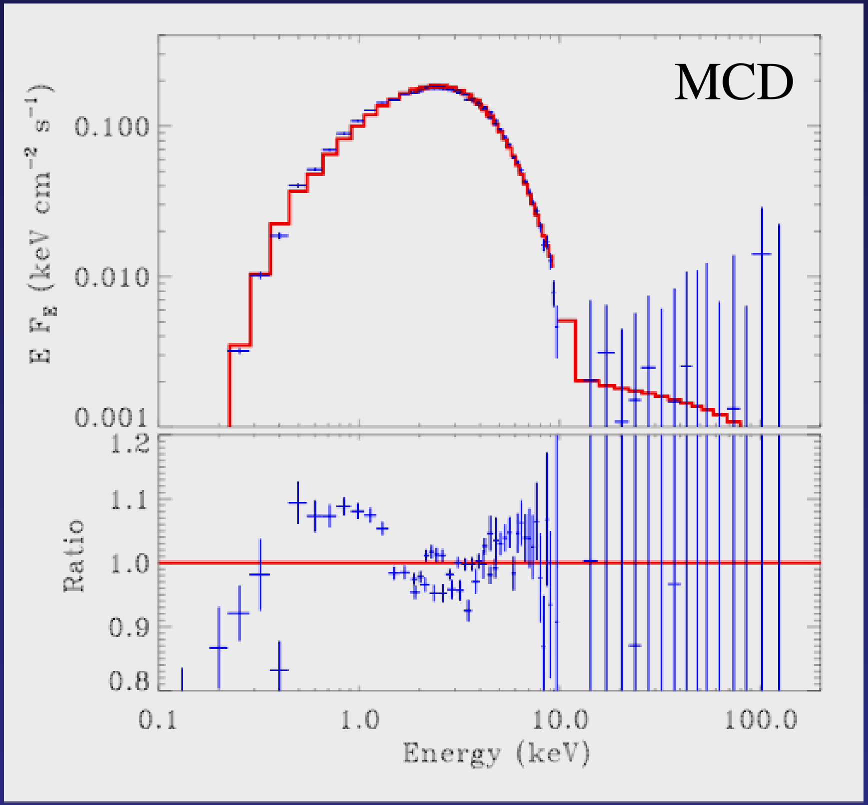
- Use conservation laws with Kerr metric to calculate one-zone model
- Full disk model is determined by ~4 parameters: M, a, L/L_{Edd}, α
- Calculate self-consistent vertical structure and radiative transfer in a series of concentric annuli
- Each annulus is determined by 3 parameters (+ assumptions): T_{eff}, Q, (g=Q z), Σ
- Calculate photon geodesics in a relativistic spacetime for an observer at inclination i (ray tracing)

Model Parameters



‘Broadband’ Fits to LMC X-3





- MCD model is too narrow -- need relativistic broadening $\Delta\chi^2 \sim 100$
- Best fit find spinning black hole with a_*=0.45, consistent with *RXTE* fits

Spectral Formation

- Depth of formation τ_*: optical depth where $(\tau_{es}\ \tau_{abs})^{1/2}\sim 1$

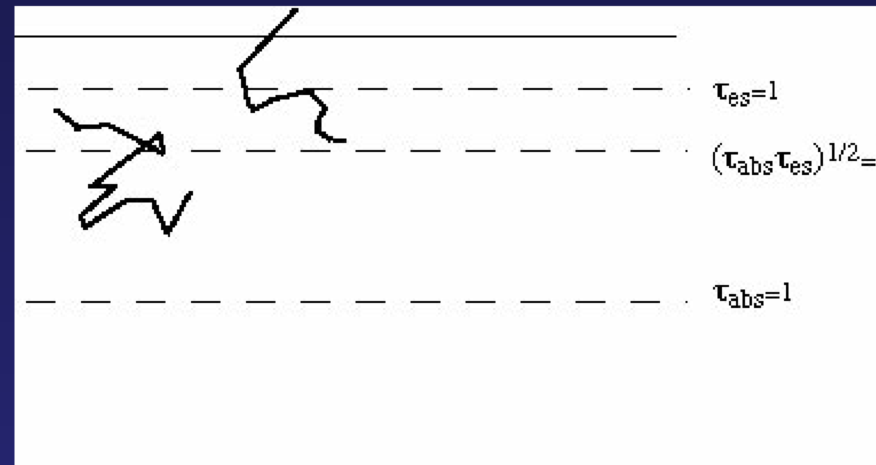
  $\tau > \tau_*$: absorbed

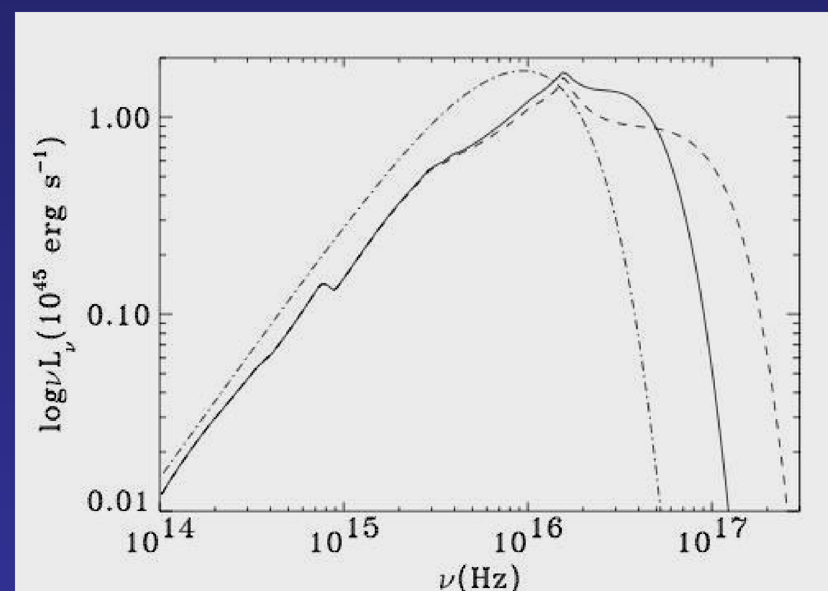
  $\tau < \tau_*$: escape

- Therefore Thomson scattering produces modified blackbody:

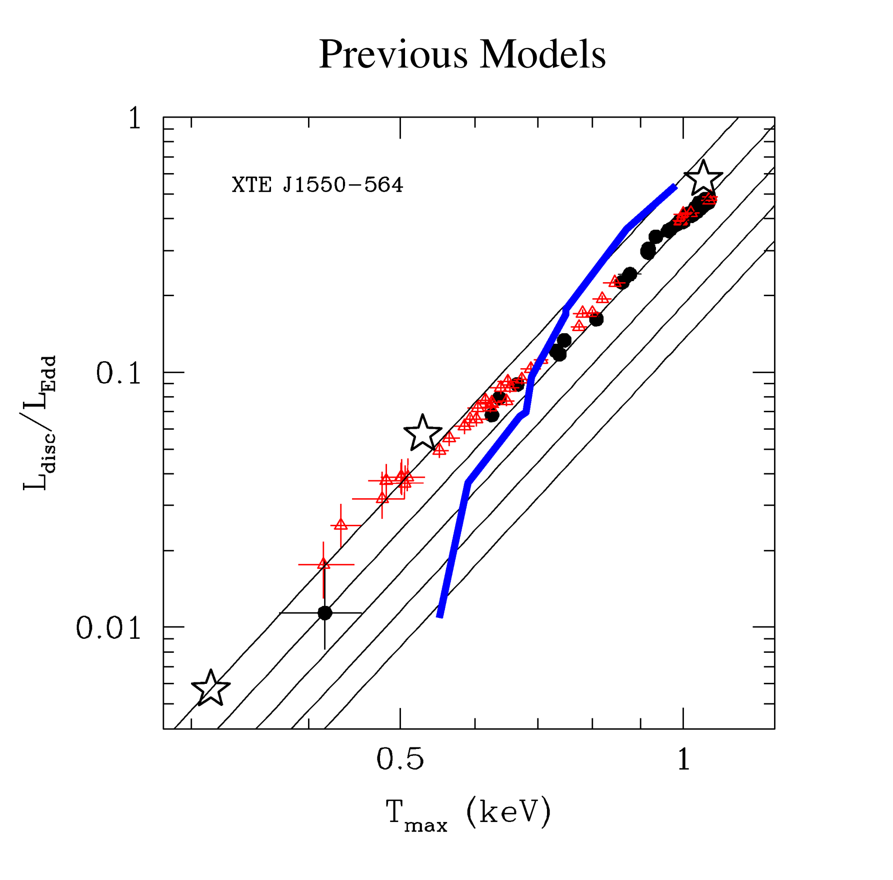
$$I_\nu \approx B_\nu \sqrt{\frac{\kappa_{abs}}{\kappa_{es}}}$$

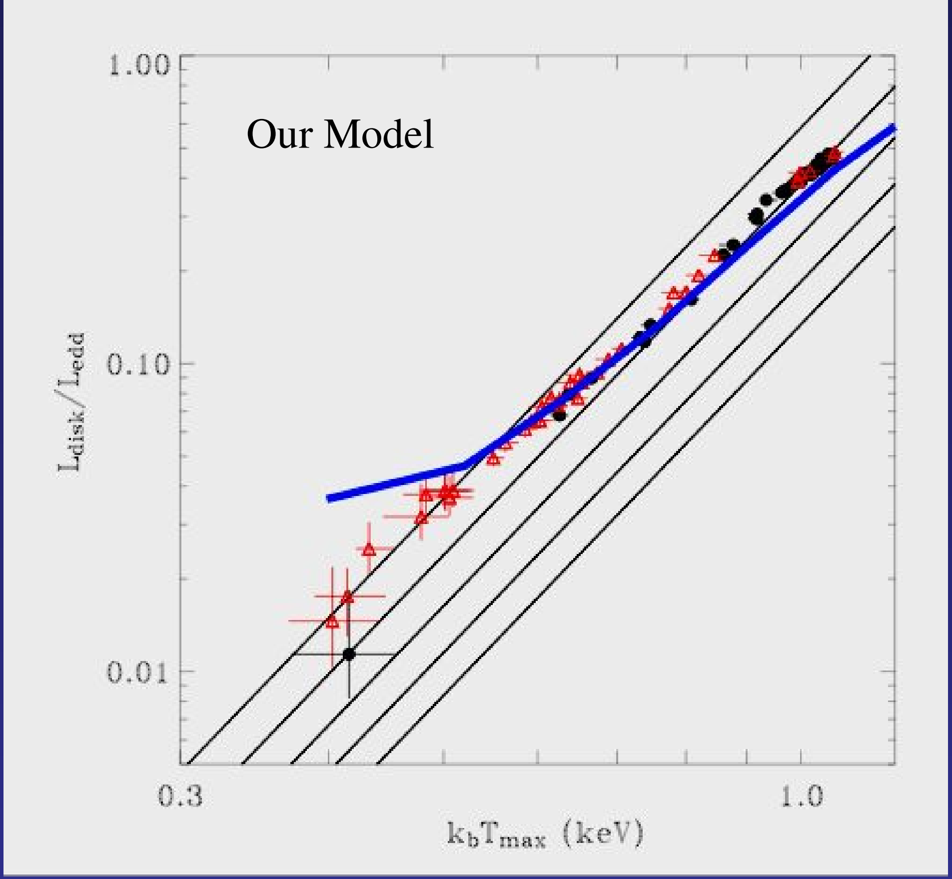
- Compton scattering gives softer Wien spectrum
- From these considerations Shimura & Takahara (1995) find f_{col}=1.7+/-0.2





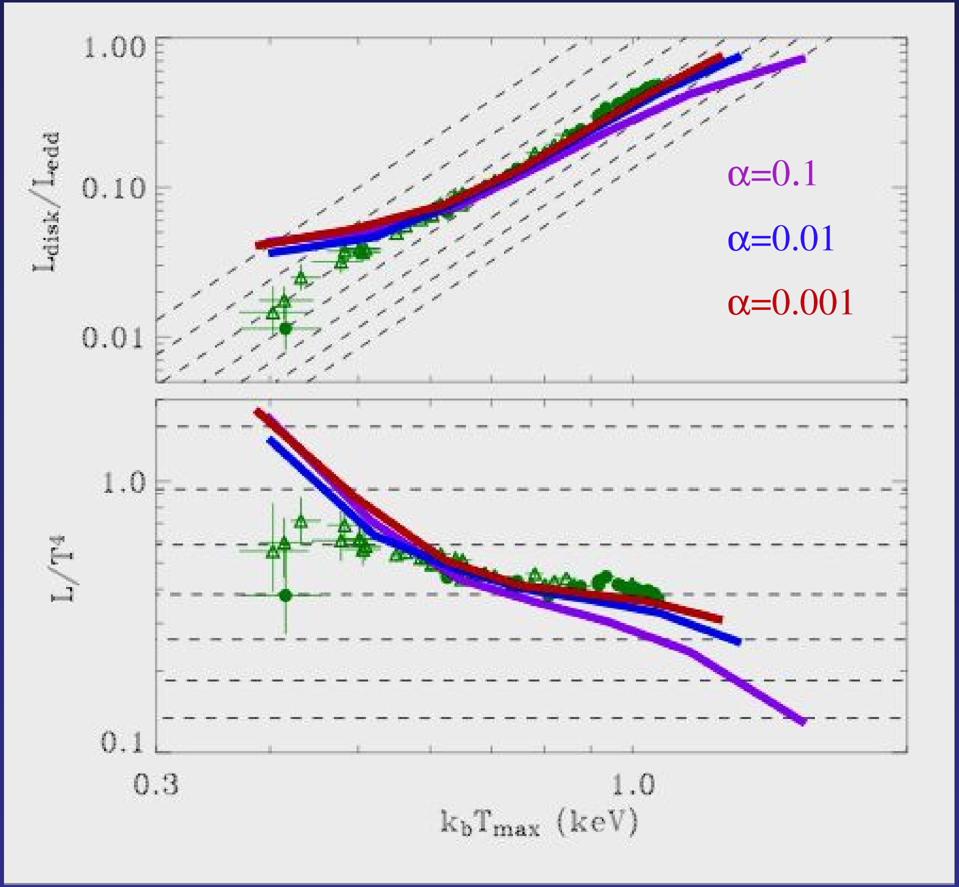
Luminosity vs. Temperature



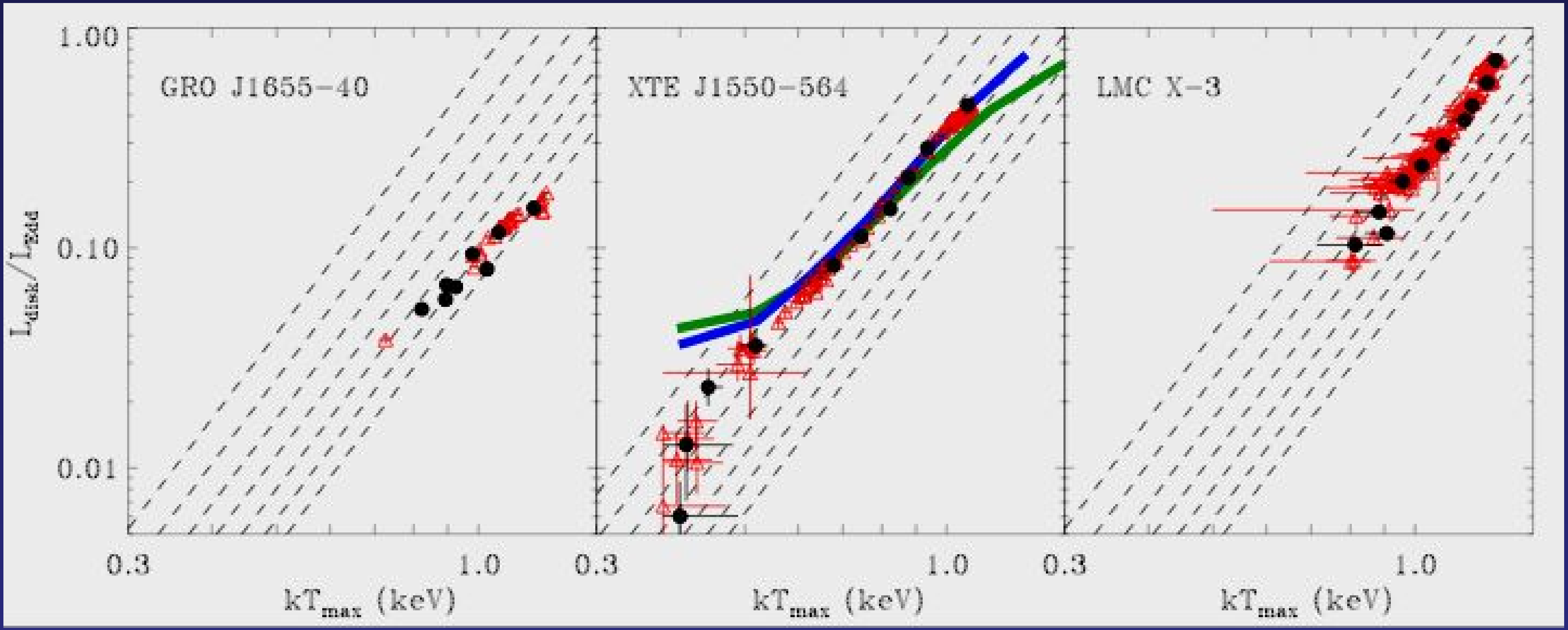


Luminosity vs. Temperature

- Slight hardening is consistent with some observations
- Allows one to constrain surface density and accretion stress
- Models become effectively optically thin at high accretion rates



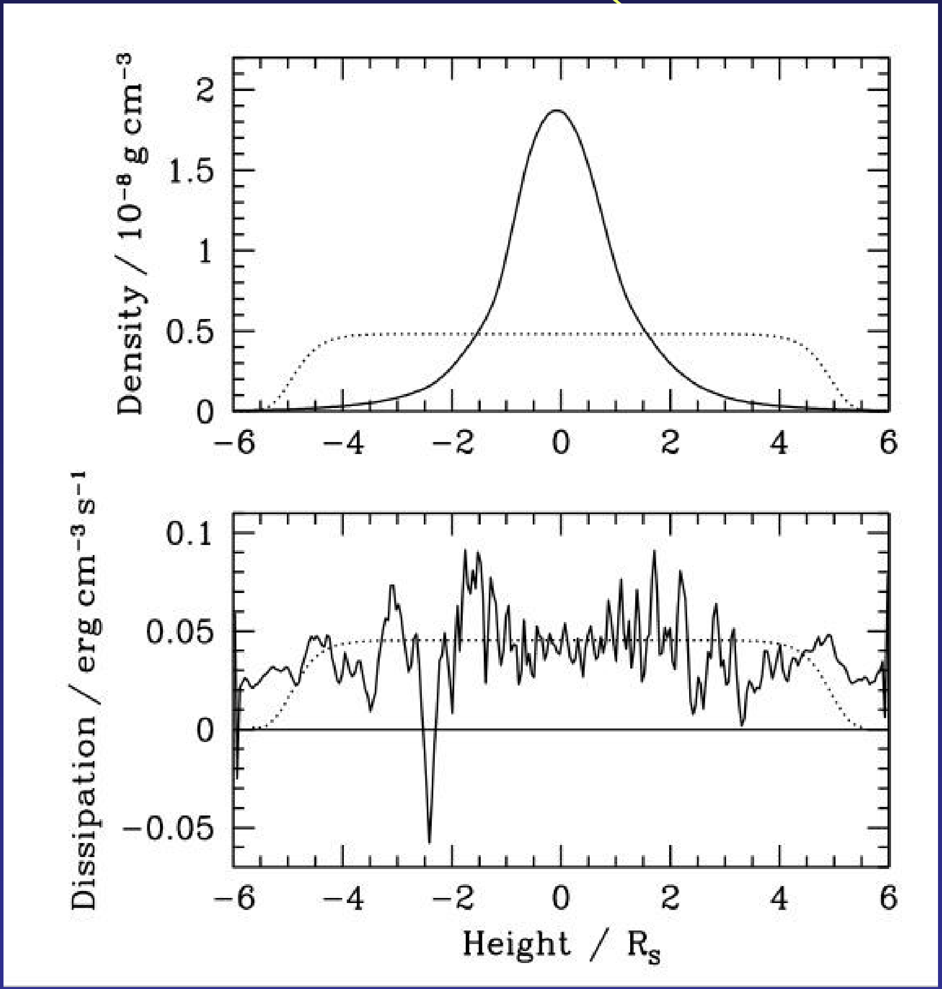
Summary of Fit Results



- Lack of hardening suggests hottest annuli remain effectively thick (especially LMC X-3)
- Models consistent with moderate spins, small torques for disk inclination = binary inclination (a_*~0.7, 0.1, 0.4)

II. Adding ‘Real’ Physics: Dissipation, Magnetic Stresses & Inhomogeneities

Local MRI Simulations (with radiaton)



- Shakura & Sunyaev (1973):

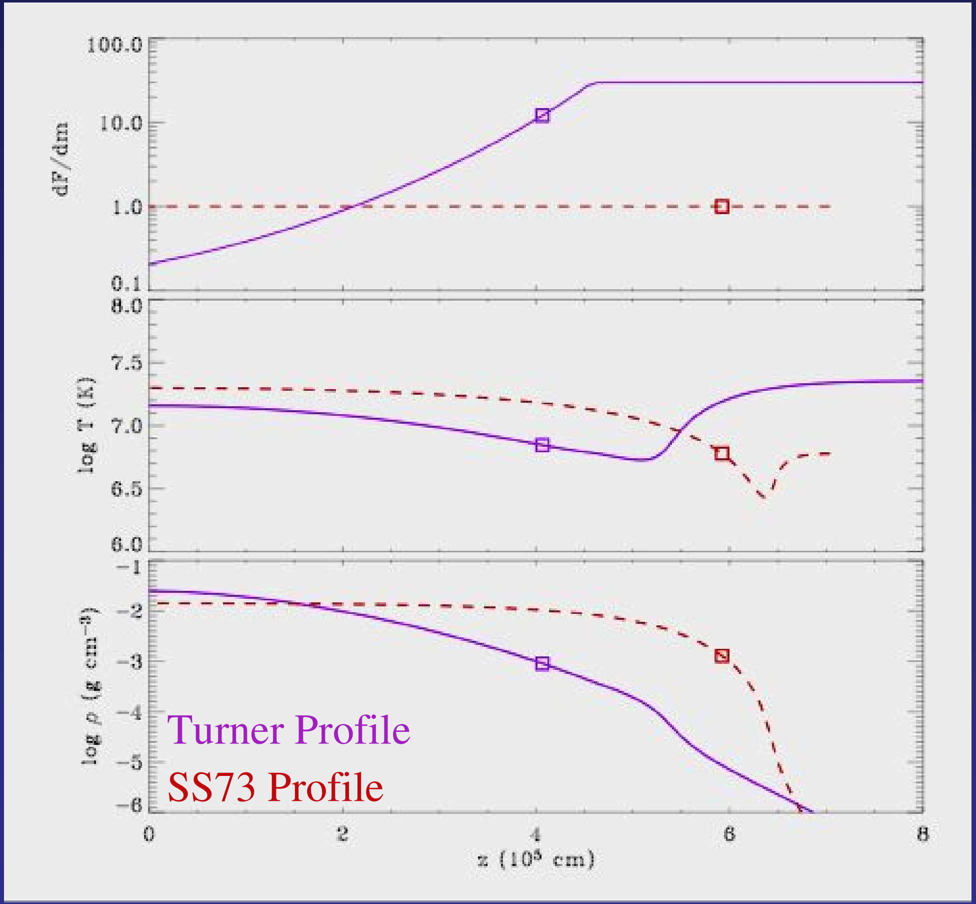
$$-\frac{dF}{dm} = \frac{1}{\rho}\frac{dF}{dz} = \frac{2\sigma T_{\rm eff}^4}{\Sigma}$$

- Turner (2004): Mass more centrally concentrated towards midplane in simulations.
- Magnetic fields produced near midplane are buoyant and dissipate near surface

Turner (2004)

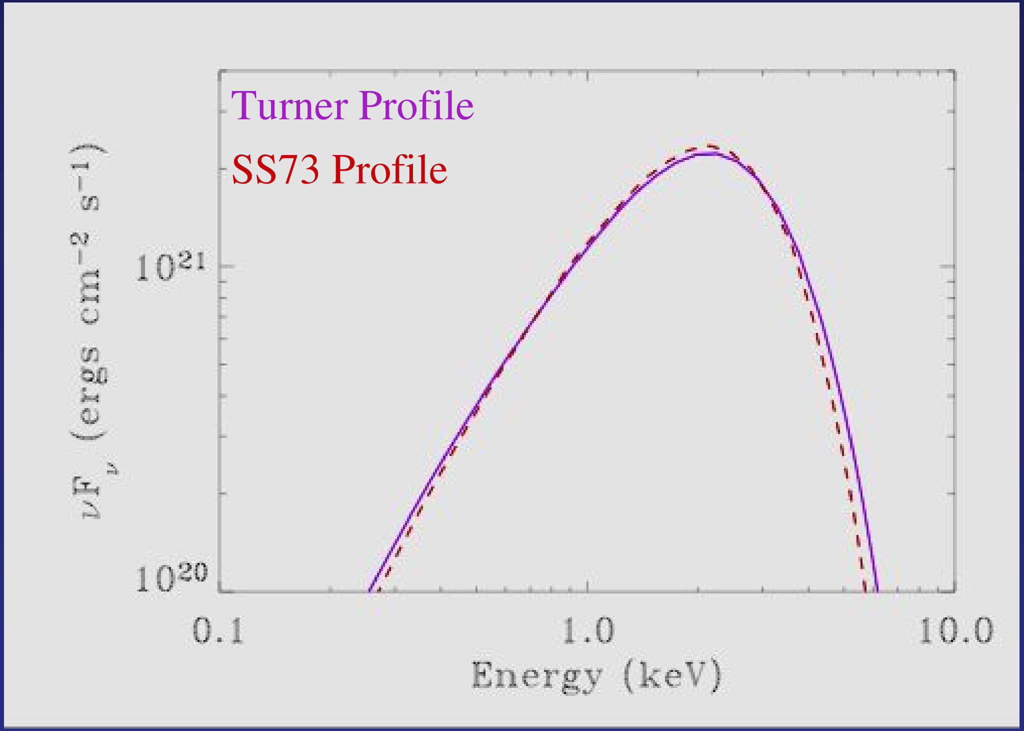
Dissipation Profile

- Modified dissipation profile changes structure significantly
- Where -dF/dm is small (large), density is larger (smaller)
- Note that T and ρ near τ^* are similar

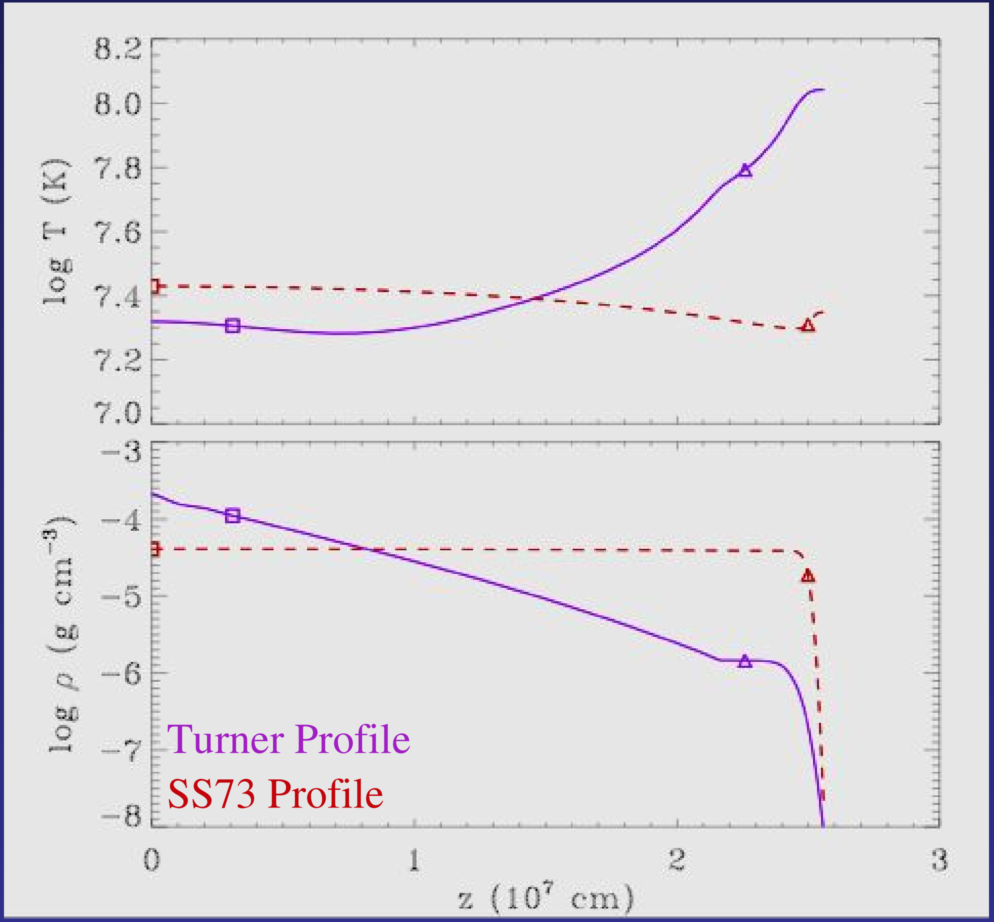


Dissipation Profile

- … but modified dissipation profile has limited affect on the spectrum.
- This particular annulus is very effectively optically thick and τ^* is close to surface

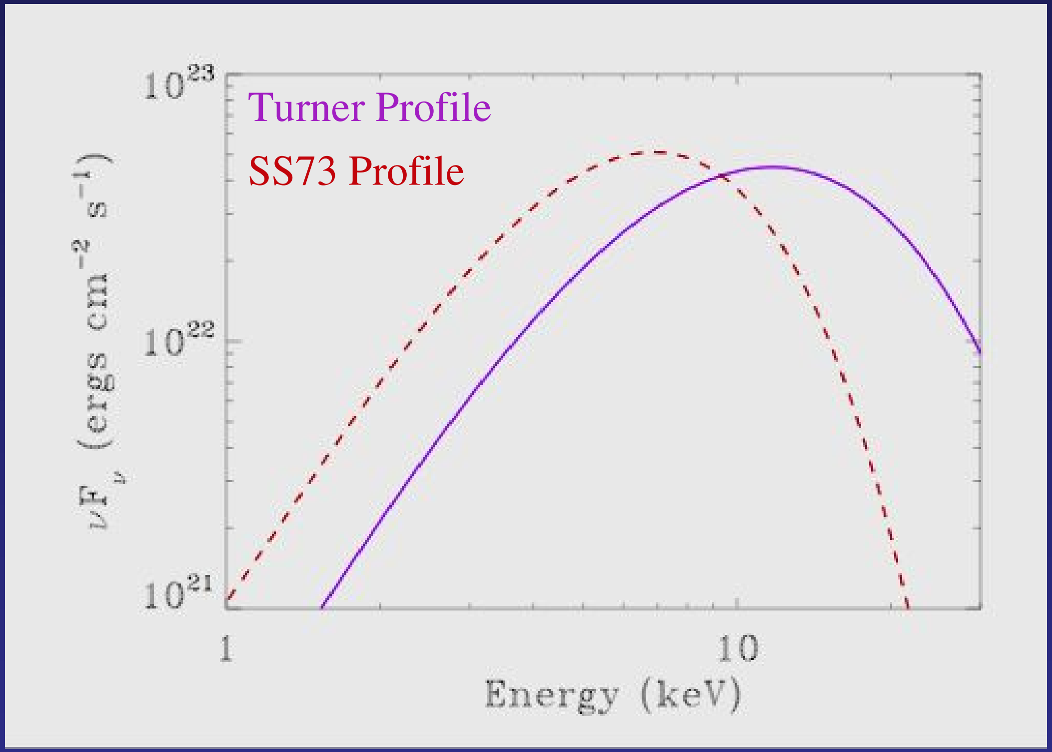


Dissipation Profile



- Consider same dissipation profile, but in an annulus that is not effectively optically thick.
- Spectrum with modified dissipation profile is effectively optically thick, but has a much greater surface temperature

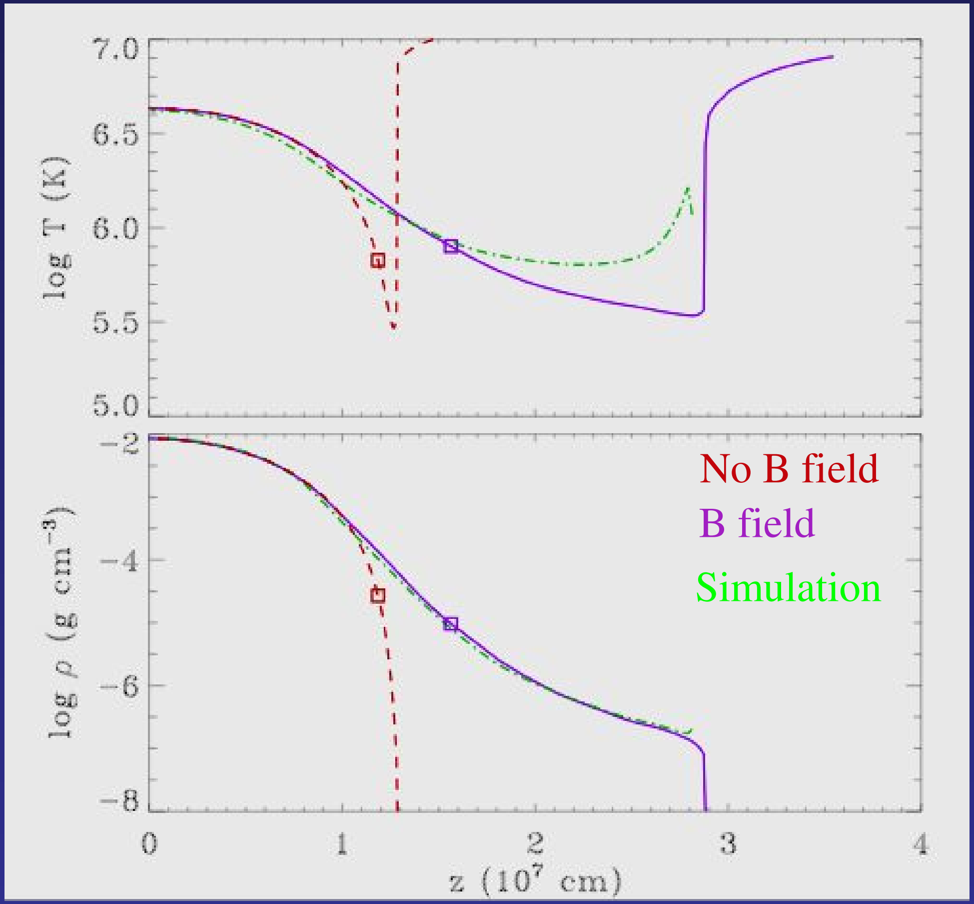
Dissipation Profile



- For this annulus, the spectra from the modified dissipation profile is considerably harder
- This will exacerbate the discrepancy between observations and models unless disks stay optically thick

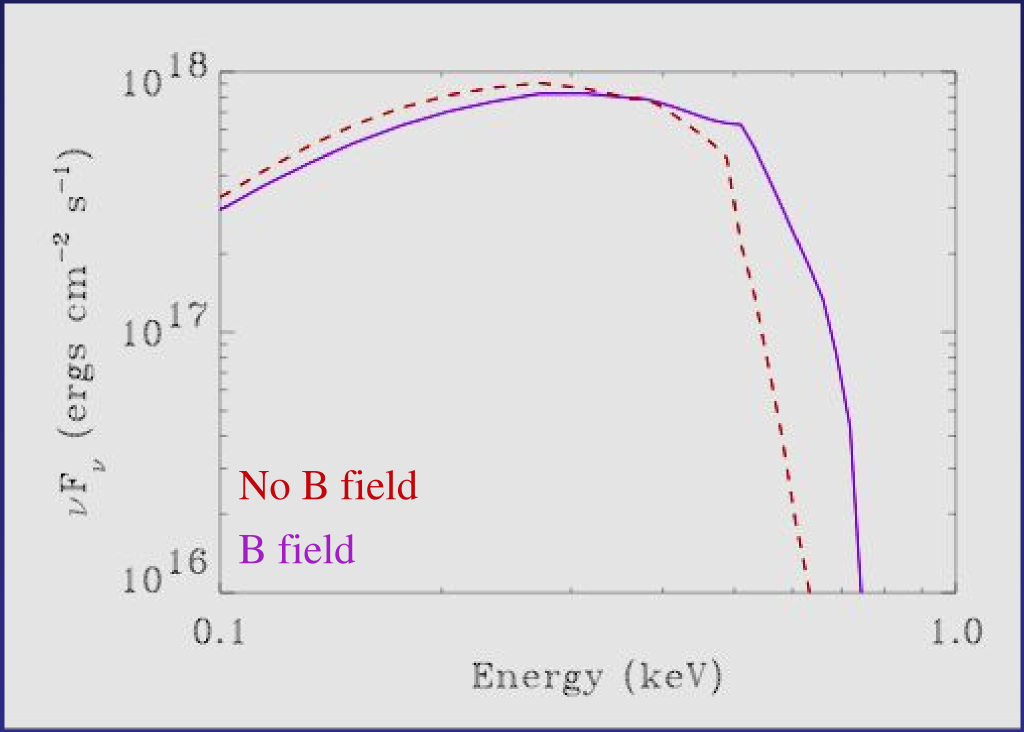
Magnetic Stresses

- $B^2/8\pi$ & dF/dm taken from simulations of Hirose, Krolik, & Stone
- Gas pressure dominated -- dF/dm has little effect on the structure
- Extra magnetic pressure support lengthens scale height h_ρ
- $\rho_* \sim \tau_*/(\kappa_{es}\, h_\rho)$

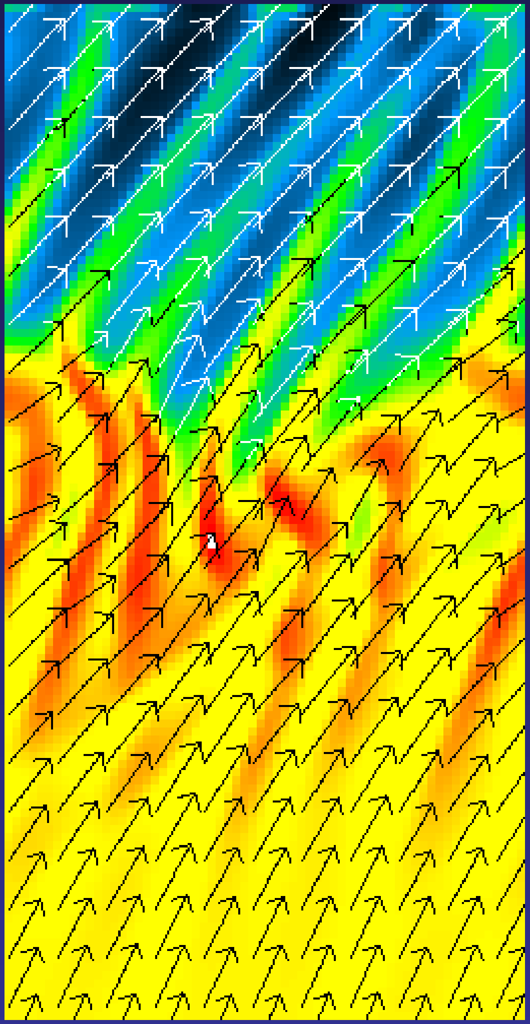


Magnetic Stresses

- Lower ρ_* and higher T_* combine to give somewhat harder spectrum
- In this case lower ρ_* alters statistical equilibrium -- lower recombination rate relative to photoionization rate give more highly ionized matter with lower bound-free opacity



Inhomogeneities

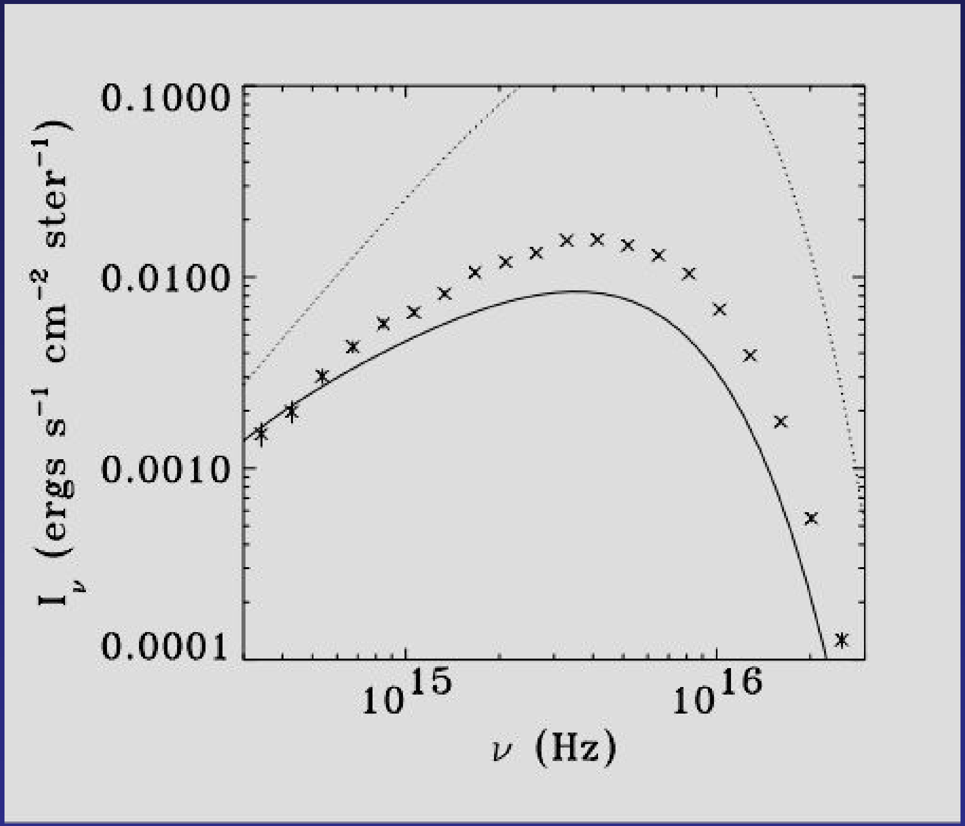


Neal Turner

- Radiation pressure dominated accretion disks expected to be homogeneous due to photon bubble instability and/or compressible MRI
- May make disk thinner and (therefore) denser (Begelman 2001, Turner et al. 2005)
- May also affect the radiative transfer…

Inhomogeneities

- 2-D Monte Carlo calculations: photon bubbles help thermalize the spectrum, making it softer
- Photon emission and absorption dominated by denser regions.



What Have We Learned?

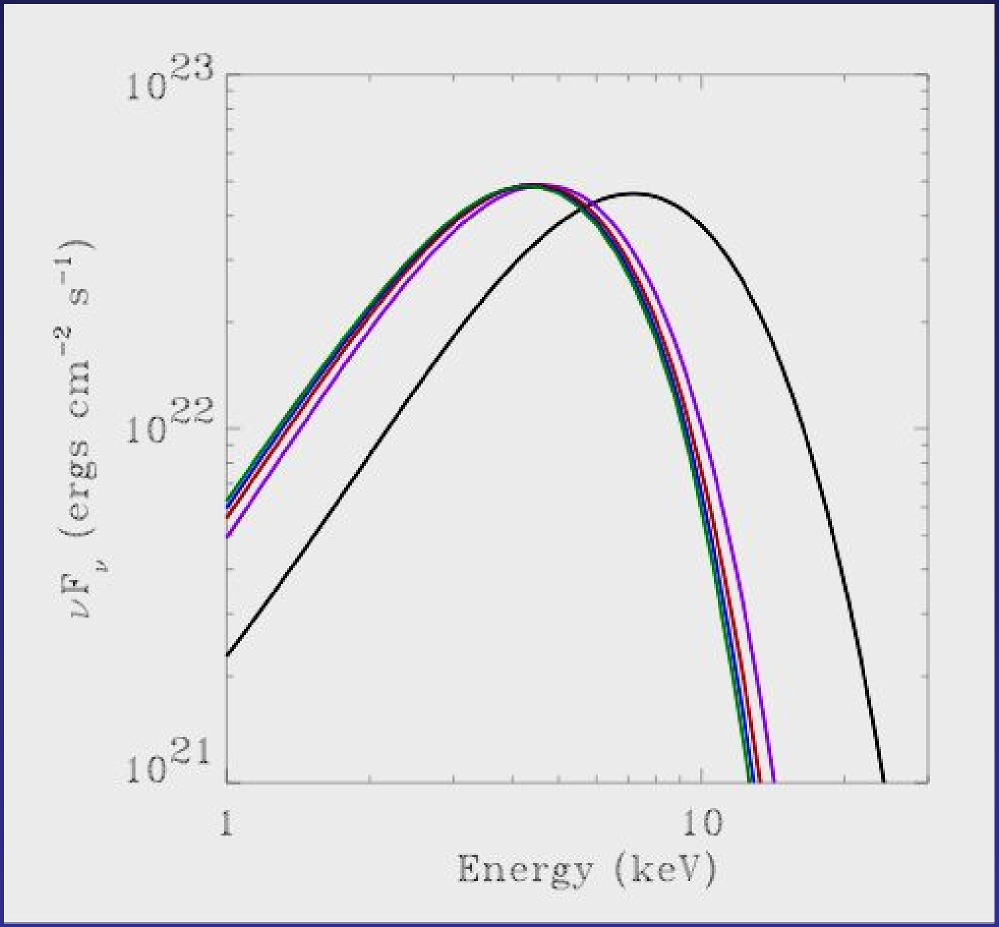
- Our detailed accretion disk models can reproduce the spectra of disk dominated BHBs (better than the MCD in LMC X-3)
- Models reproduce the observed evolution with luminosity; spectral modeling may constrain the nature of angular momentum transport and black hole spin (torques?)
- Dissipation, magnetic stresses, and inhomogeneities may affect the spectra -- more simulations or analytical progress needed.

Non-aligned Jet

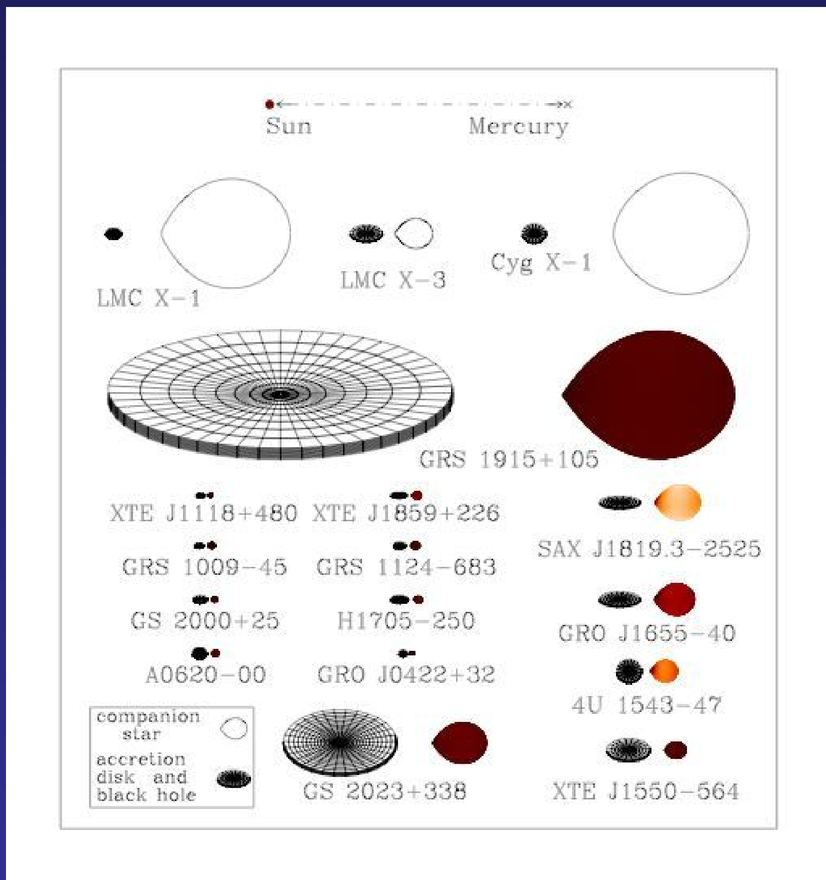
- XTE J1550-564 is a microquasar
- Hannikainen et al. (2001) observe superluminal ejections with v > 2 c
- Ballistic model: $$\beta_{\rm ap} = \frac{\beta \sin\theta}{1-\beta\cos\theta} \Rightarrow \theta < 53^\circ$$
- Orosz et al. (2002) found $i=72^{o}$
- Non-aligned jets not uncommon -- usually assumed that BH spin differs from binary orbit and inner disk aligns with BH -- Bardeen-Petterson effect
- Best fit inclination, spin: $i=43^{o}$, a=0.44

Spectral Dependence on Surface Density

- Spectra largely independent of S for large surface density (Σ >~ 10^3 g/cm^2)
- As disk becomes marginally effectively thin, spectra become sensitive to Σ and harden rapidly with decreasing Σ



Binaries Provide Independent Constraints on Models

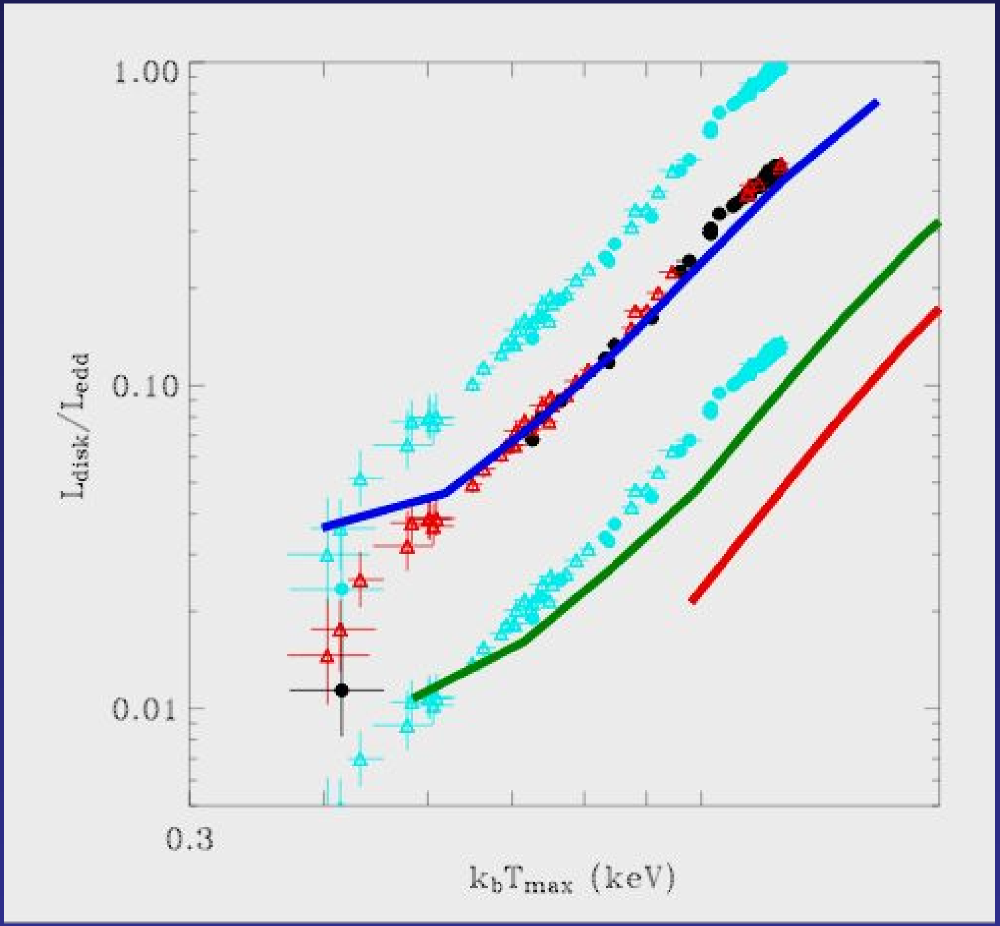


- Orosz and collaborators derive reasonably precise estimates from modeling the light curve of secondary
- e.g. XTE J1550-564:

$$M = 10\,(9.7 - 11.6)\,M_\odot$$
$$i = 72^\circ\,(70.8^\circ - 75.4^\circ)$$
$$D = 5.3\,(2.8 - 7.6)\,\mathrm{kpc}$$

Luminosity vs. Temperature

- Measured binary properties limit parameter space of fits
- Simultaneous fits to multiple observations of same source constrain spin/torque
- Spectra are too soft to allow for extreme spin/large torques

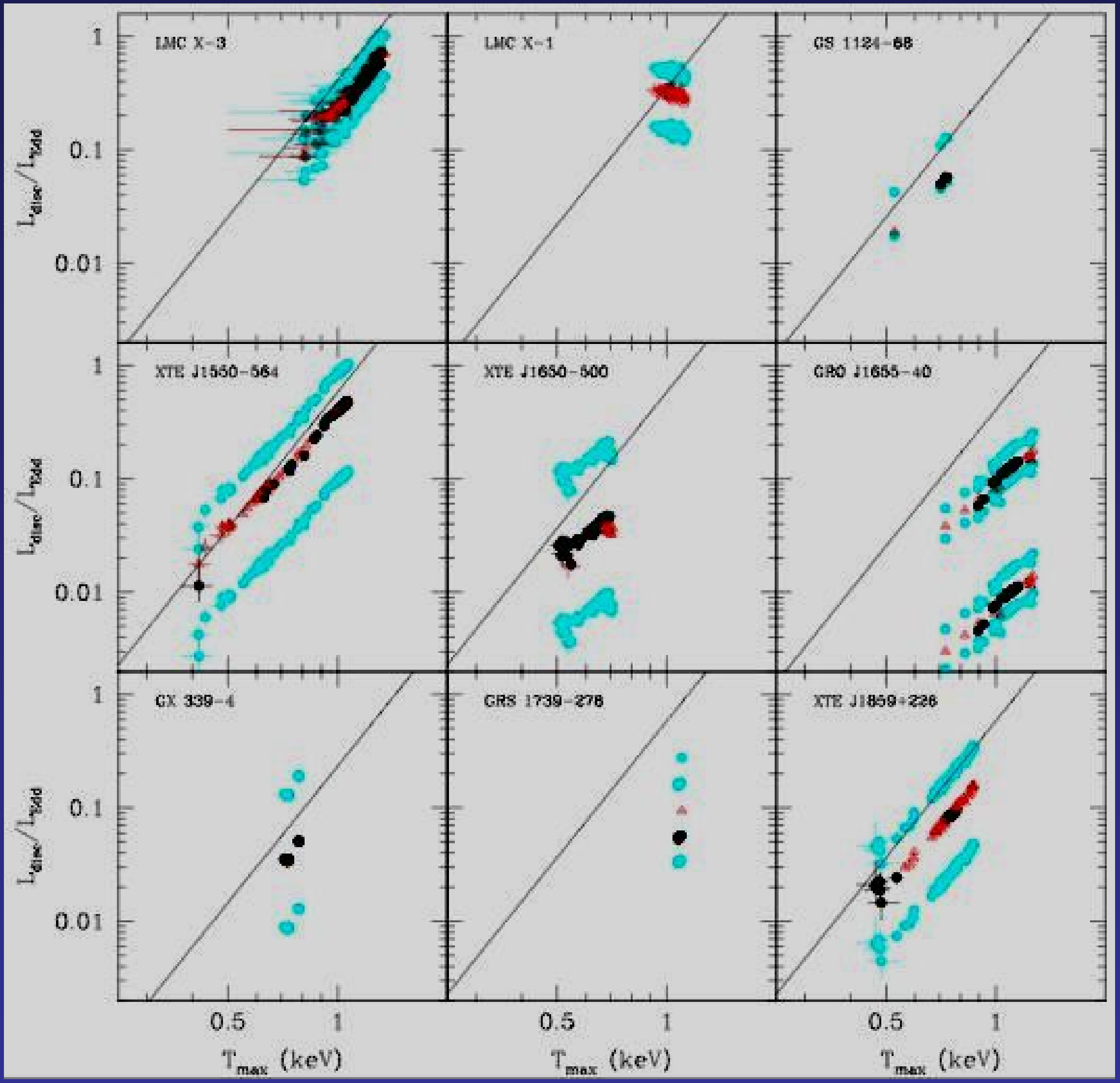


Stellar Atmospheres: Disk Annuli vs. Stellar Envelopes

- The spectra of stars are determined by T_{eff}, g, and the composition
- Annuli are determined by, T_{eff}, Q (where g=Q z), S, the composition, and the vertical dissipation profile: F(m)
- T_{eff}, Q, and S can be derived from radial disk structure equations
- Standard assumption is:

$$-\frac{dF}{dm} = \frac{2\sigma T_{\rm eff}^4}{\Sigma}$$

Luminosity vs. Temperature

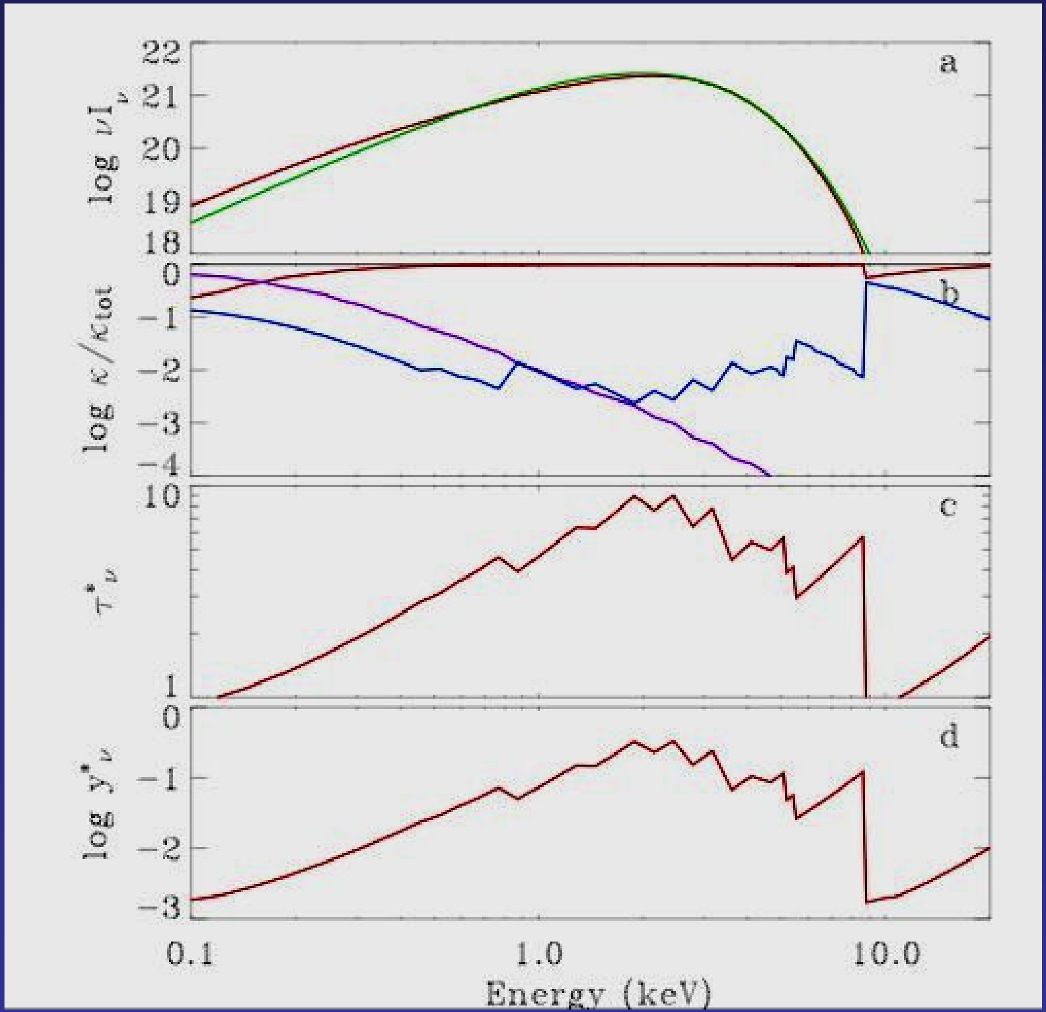


Gierlinski & Done 2004

Effect of bound-free opacity

- Bound-free opacity decreases depth of formation: τ^*
- $y^*_\nu = \frac{4kT^*}{m_e c^2} \tau^{*2}_\nu < 1$
- Absorption opacity approximately grey
- Spectrum still approximated by diluted blackbody:

$$I_\nu \approx B_\nu \sqrt{\frac{\kappa_{abs}}{\kappa_{es}}} \approx B_\nu \times \text{const.}$$



The Multicolor Disk Model (MCD)

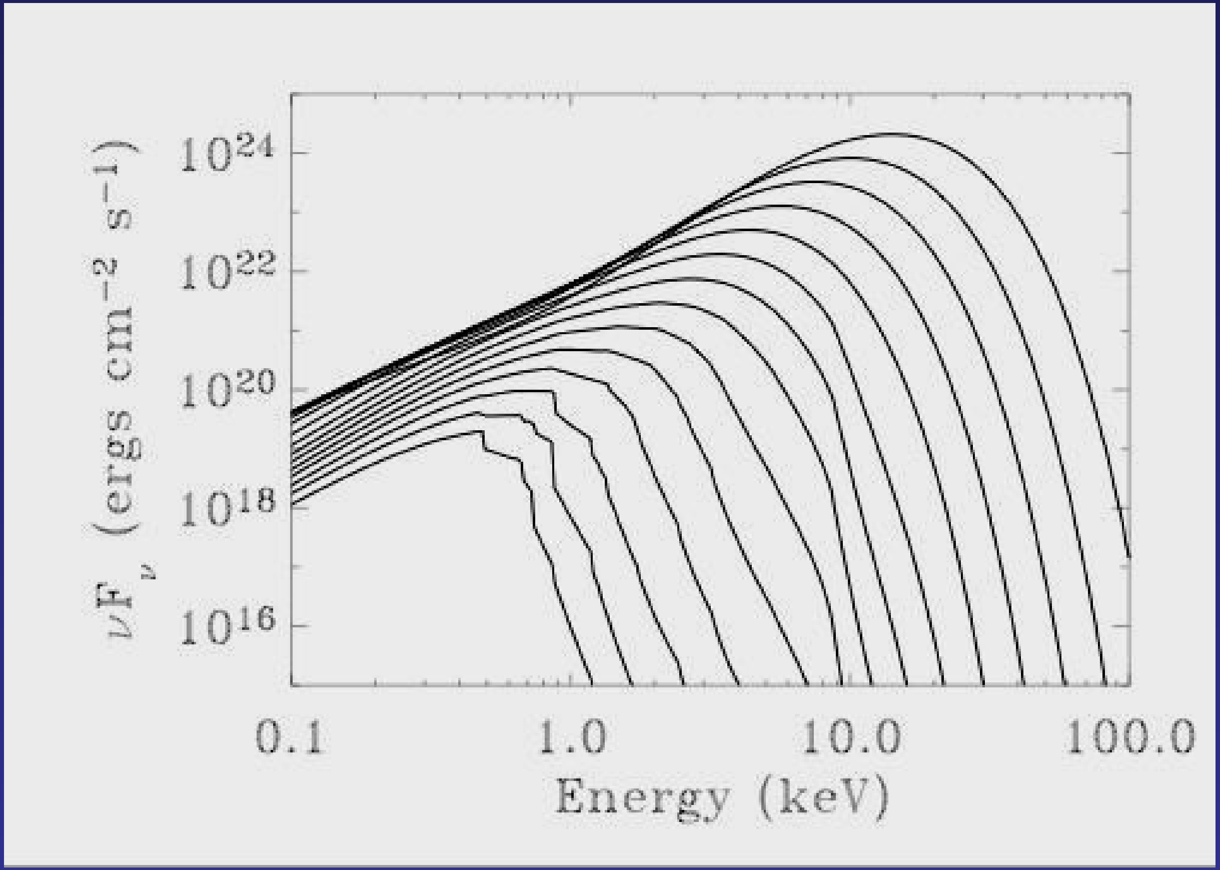
- Consider simplest temperature distribution:

$$\pi R^2 \sigma_{\rm sb} T_{\rm eff}^4 \sim \frac{GM\dot{M}}{R} \Rightarrow T_{\rm eff}^4 \propto R^{-3/4}$$

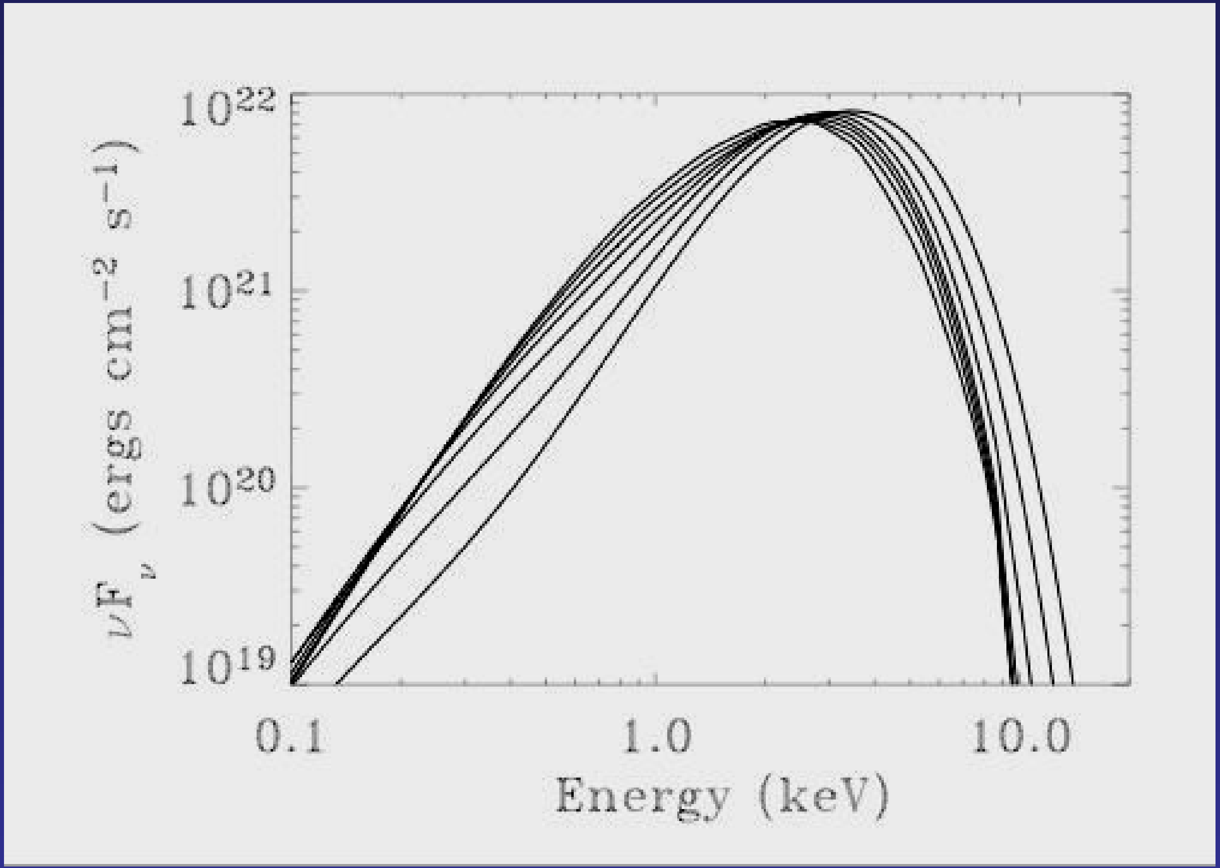
- Assume blackbody and integrate over R replacing R with T ($T_{max} \sim f_{col} T_{eff}$):

$$I_\nu = \frac{8\pi R_{\rm in}^2 \cos i}{3D^2 f_{\rm col}^4} \int_0^{T_{\rm max}} B_\nu(T) \left(\frac{T}{T_{\rm max}}\right)^{-11/3} \frac{dT}{T_{\rm max}}$$

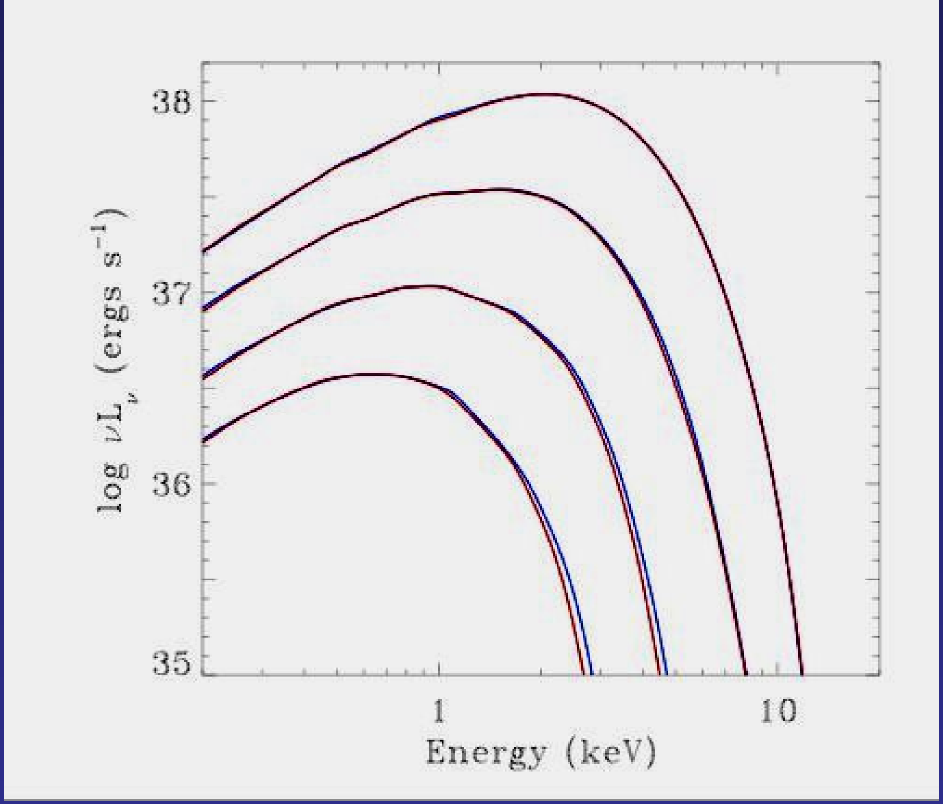
Effective Temperature: T_{eff}



Gravity Parameter: Q



Comparison Between Interpolation and Exact Models



- Interpolation best at high L/L_{edd}
- Exact: Blue curve

  Interpolation: Red Curve