Continuum Spectra: Another Window on the Horizon Scale Astrophysics in Accreting Black Hole Systems

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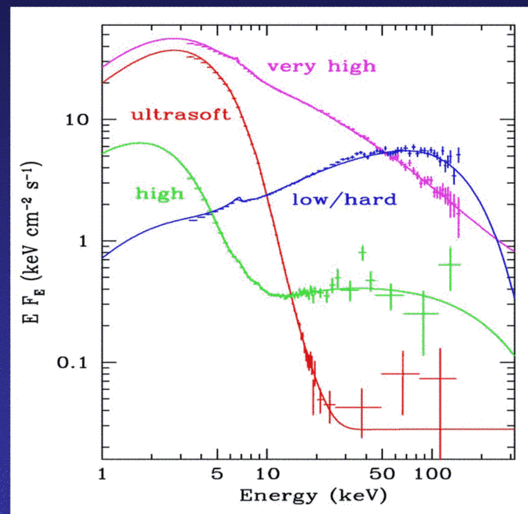
Understanding Luminous Accretion

- Are thin disk models sufficient? Are they even close?
- What is the distribution of BH spins?
- Are there large torques on the disk?
- What is the nature of the stress?
- Is there evidence for advection?
- What else is going on? photon bubbles, warps, winds, …

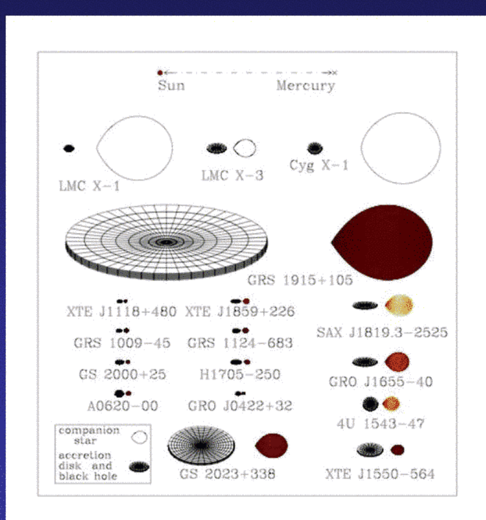
Spectral States of BHBs

- Spectral states specified by relative contributions of thermal and non-thermal emission
- High/Soft state is dominated by thermal component believed to come from disk



Done & Gierlinski 2004

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:

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

The MCD model

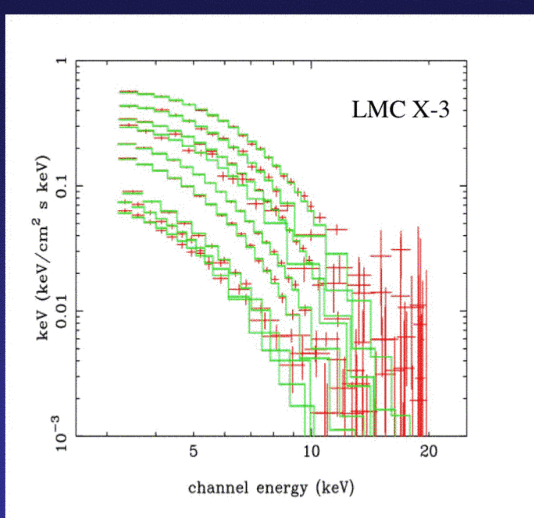
- Consider simplest temperature distribution:

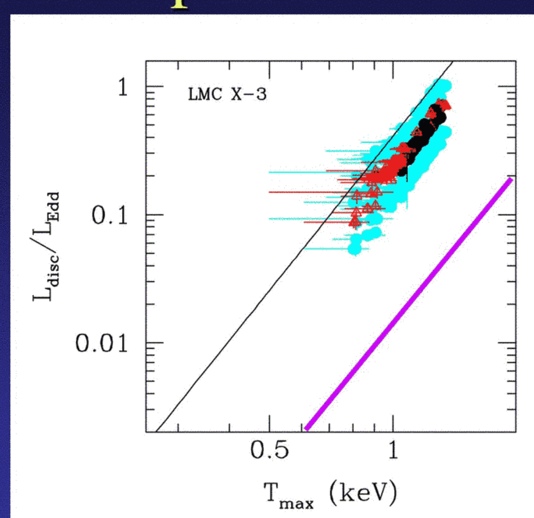
$$\pi R^2 \sigma T_{\rm eff}^4 \approx \frac{GM\dot{M}}{R} \Rightarrow T_{\rm eff} \propto R^{-3/4}$$

- Assume diluted blackbody and integrate over R replacing R with T:

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

Disk Dominated Spectra



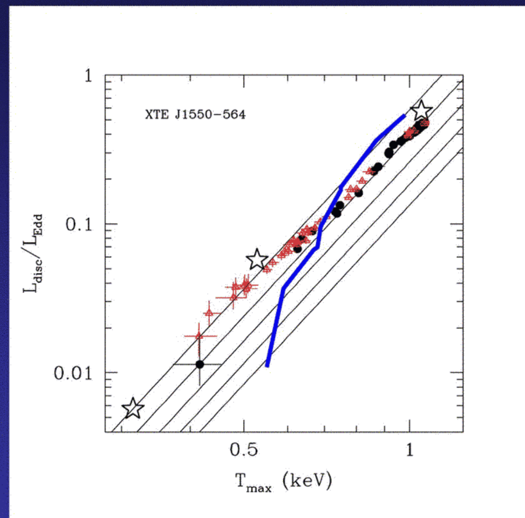


Gierlinski & Done 2004

- L a T^4 suggests f_{col} and emitting area are constant

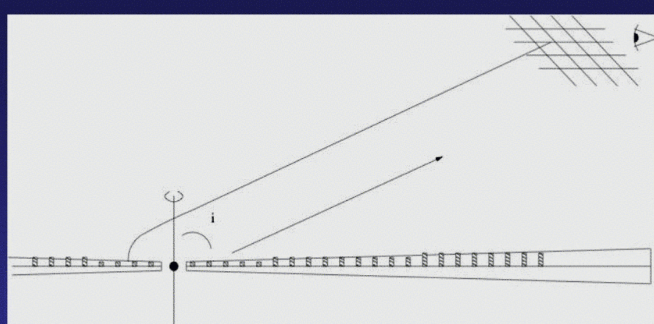
Comparison with Other Spectral Models

- Previous models provide mixed results
- Shimura & Takahara (1995): stars
- Merloni, Fabian & Ross (2000): blue curve



Gierlinski & Done 2004

Our Models, Briefly



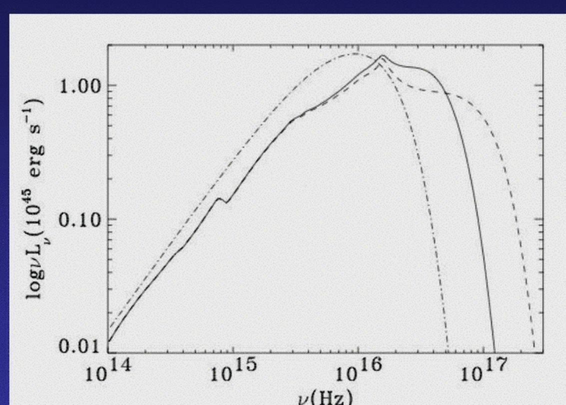
- Calculate photon geodesics in relativistic spacetime
- Use fully relativistic disk structure equations in Kerr metric
- Calculate self-consistent vertical structure and radiative transfer in each annulus or interpolate on table
- Model is determined by 5 (7) parameters: M, a, i, L/L_{Edd}, α ($\Delta\eta$, z)

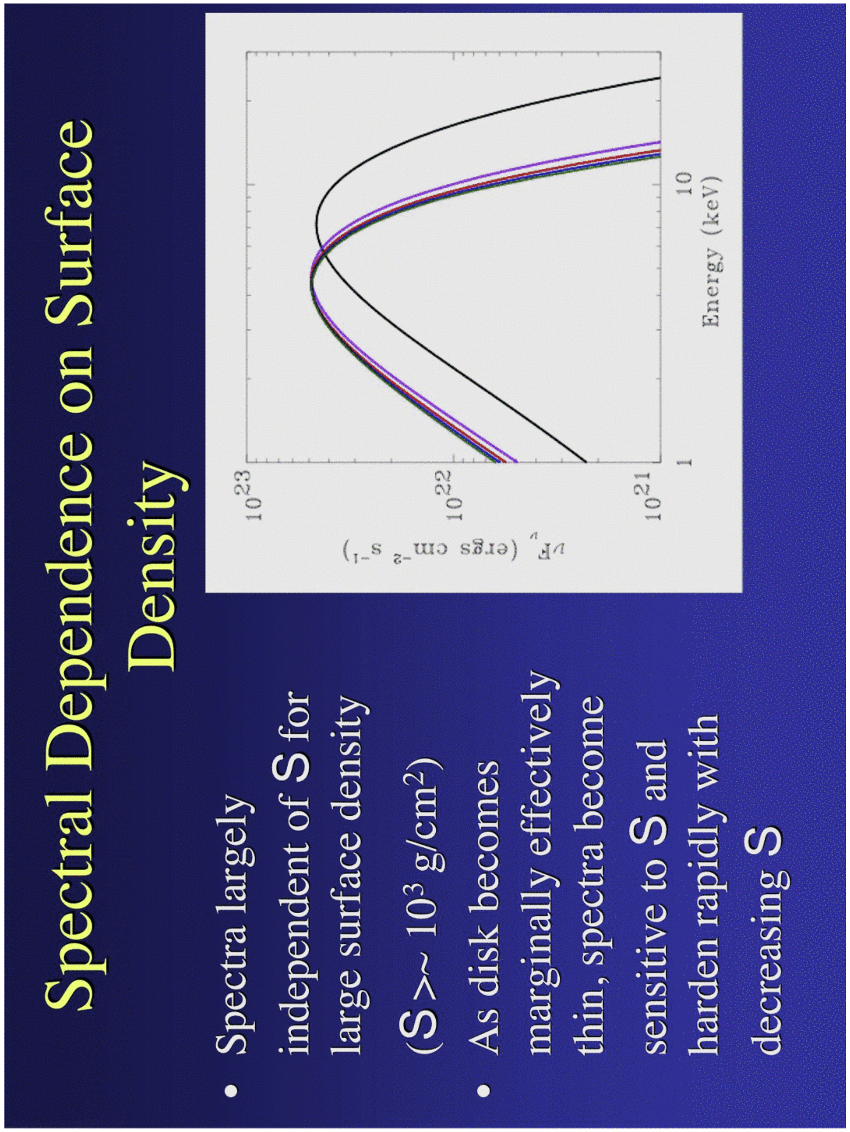
Stellar Atmospheres: Disk Annuli vs. Stellar Envelopes

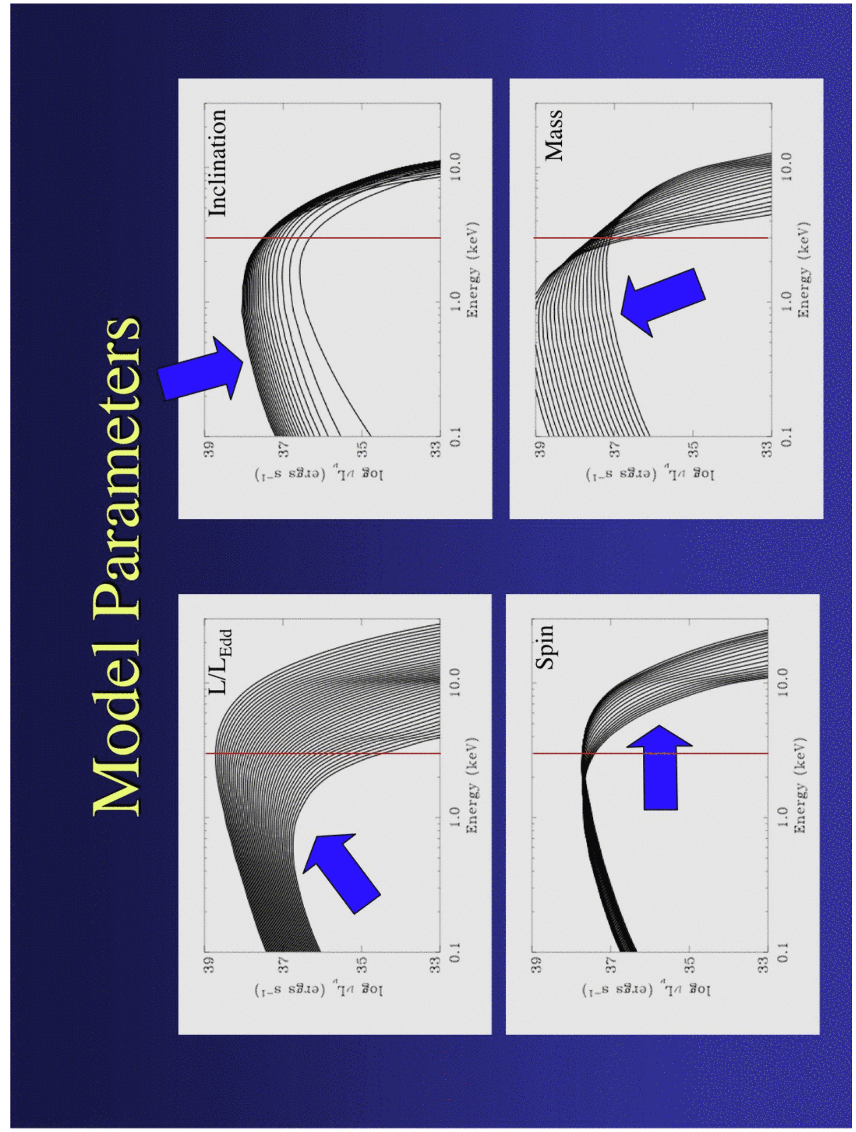
- The spectra of stars are determined by T_{eff}, g, and the composition
- Annuli are determined by, T_{eff}, Q (where g=Q z), S, the composition, and the vertical dissipation profile: F(m)
- T_{eff}, Q, and S can be derived from radial disk structure equations
- Standard assumption is: $\frac{dF}{dm} = \frac{\sigma T_{\rm eff}^4}{m_0}$

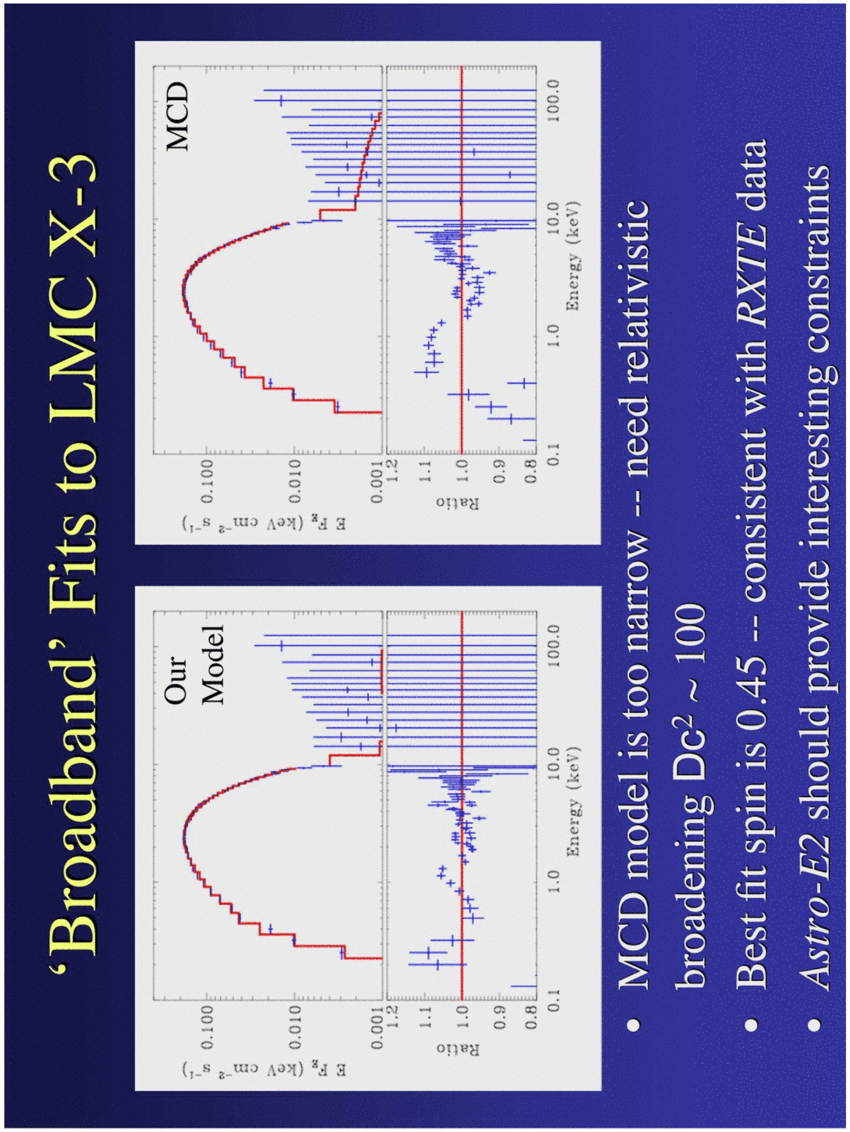
Spectral Formation

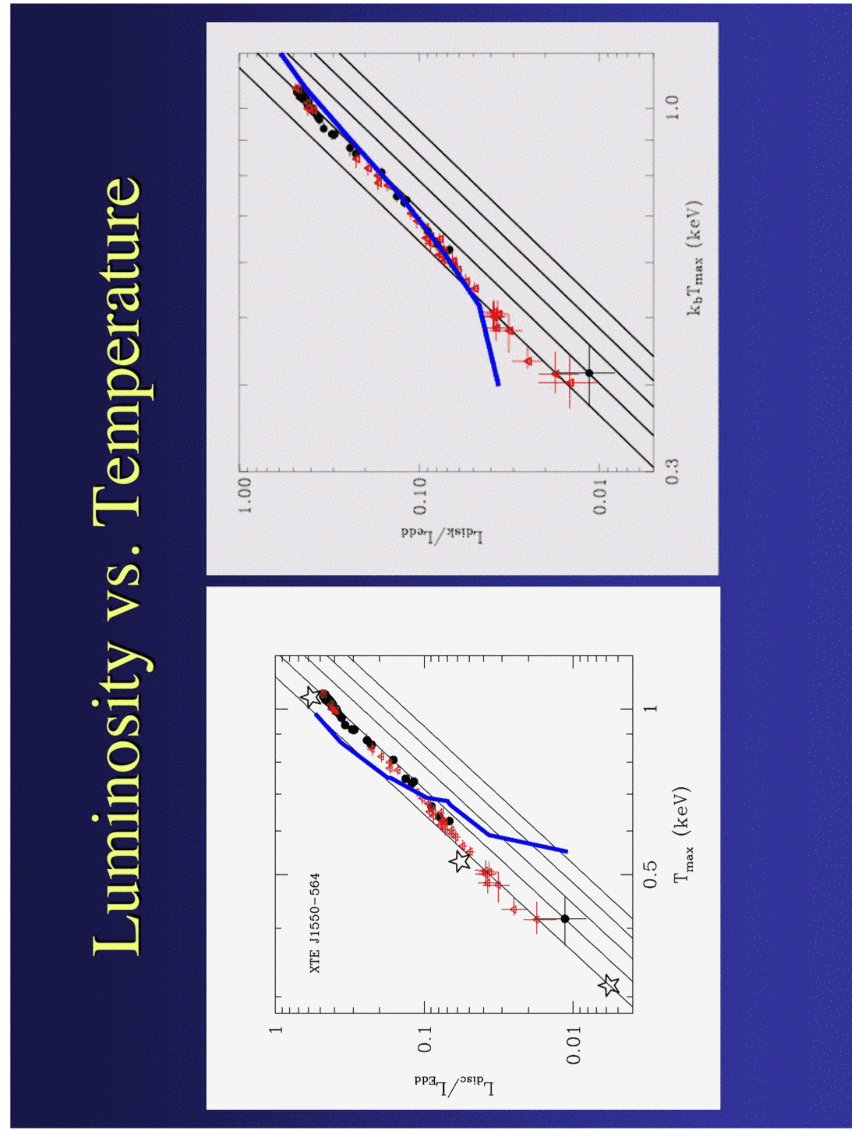
- Depth of formation τ^*: optical depth where $(\tau_{es}\,\tau_{abs})^{1/2}=1$
  - $\tau > \tau^*$: absorbed
  - $\tau < \tau^*$: escape
- Thomson scattering and/or temperature gradients: modified blackbody $I_\nu \approx B_\nu \sqrt{\frac{\kappa_{\rm abs}}{\kappa_{es}}}$
- Compton scattering: softer Wien spectrum
- Shimura & Takahara (1995): f_{col}=1.7+/-0.2




Spectral Dependence on Surface Density
Spectra largely independent of S for large surface density (S>~ 10^3 g/cm^2)
As disk becomes marginally effectively thin, spectra become sensitive to S and harden rapidly with decreasing S
νF_ν (ergs cm^{-2} s^{-1})
10^{23}
10^{22}
10^{21}
1
10
Energy (keV)

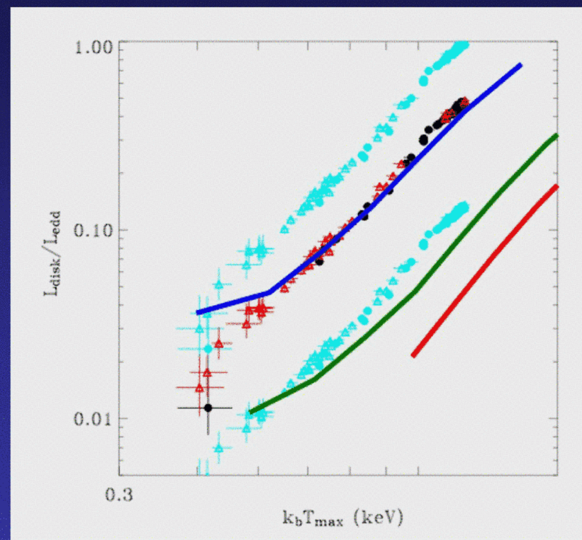

Model Parameters
L/L$_{Edd}$
Inclination
Spin
Mass
log νL_ν (ergs s^{-1})
39
37
35
33
0.1
1.0
10.0
Energy (keV)


'Broadband' Fits to LMC X-3
Our Model
MCD
Energy (keV)
Ratio
E F$_E$ (keV cm^{-2} s^{-1})
• MCD model is too narrow -- need relativistic broadening Dc^2 ~ 100
• Best fit spin is 0.45 -- consistent with *RXTE* data
• *Astro-E2* should provide interesting constraints


Luminosity vs. Temperature
XTE J1550-564
T_{max} (keV)
L_{disc}/L_{Edd}
k_bT_{max} (keV)
L_{disk}/L_{edd}

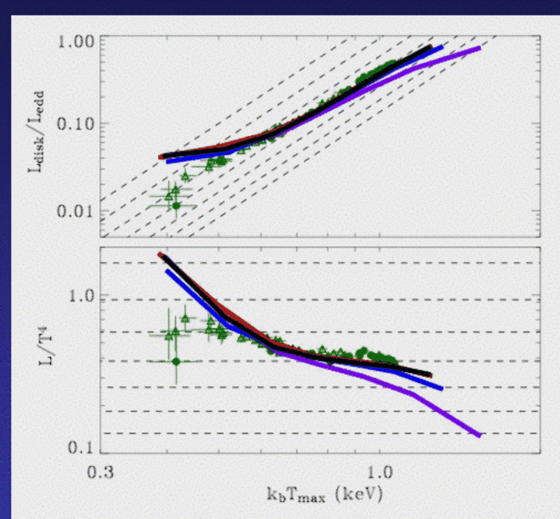
Luminosity vs. Temperature

- 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

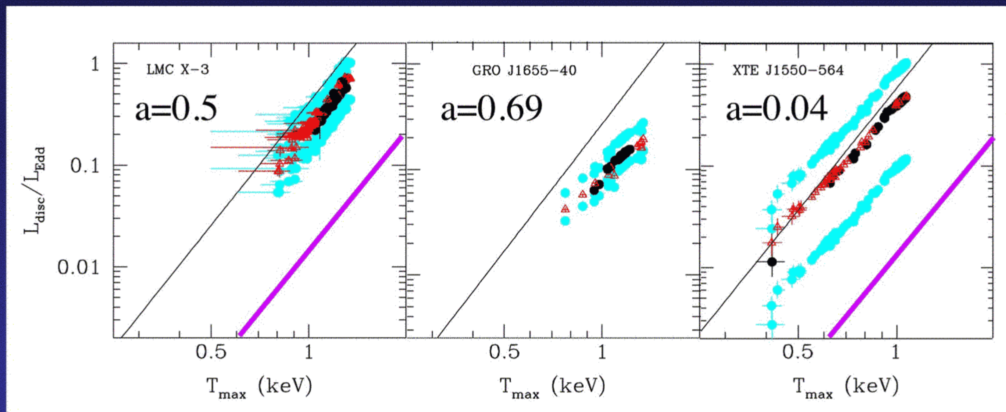


Luminosity vs. Temperature

- Slight hardening in the models is consistent with some observations
- Allows one to constrain surface density and possibly stress
- Models effectively thin where advection should become increasingly important



Fit Results: Spins, Torques, and Surface Densities



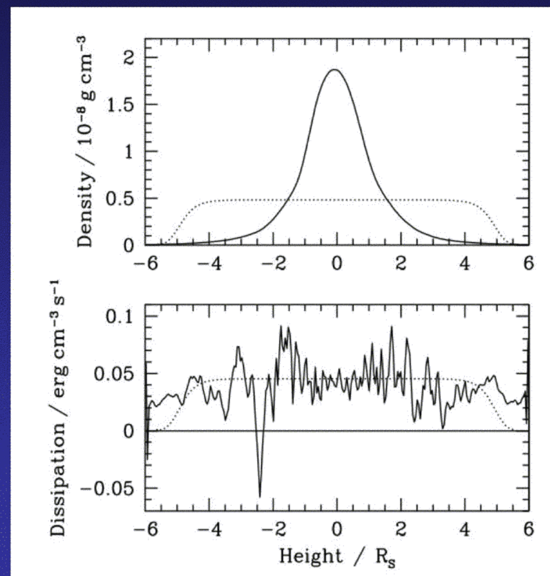
- Models inconsistent with extreme spin and large torques
- Lack of hardening suggests hottest annuli remain effectively thick (especially LMC X-3)

Non-aligned Jet

- XTE J1550-564 is a microquasar
- Hannikainen et al. (2001) observe superluminal ejections with v > 2 c
- Ballistic model: $\beta_{ap} = \frac{\beta \sin\theta}{1 - \beta\cos\theta} \Rightarrow \theta < 53^\circ$
- 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

Spectra Based on 'Real' Physics

- Vertical structure in simulations is significantly different from Shakura & Sunyaev (1973) solution
- Significant dissipation in the low density surface regions



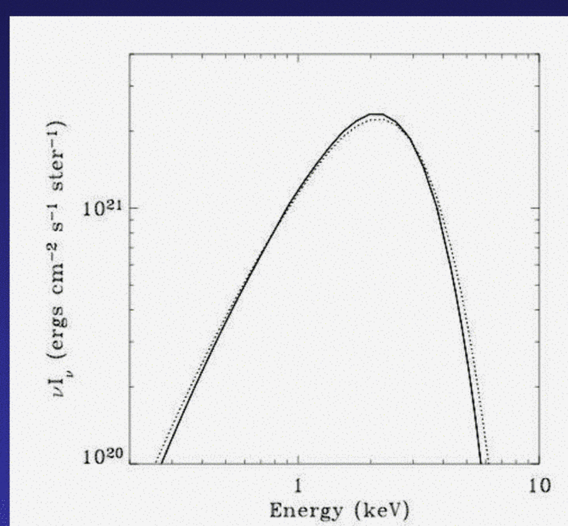
Turner 2004

Dissipation Profile: F(m)

- Usual assumption:

$$\frac{dF}{dm} = \frac{\sigma T_{\rm eff}^4}{m_0}$$

- Currently have only one simulation: 100 R_s in 10^8 solar mass BH -- more dissipation at low m
- Fit numerical profile and scale to 10 solar mass BH



Conclusions

- Thin disk model provides a good fit to broadband disk dominated spectrum of LMC X-3
- No evidence for extreme spin/strong torques -- spectra are too soft at inferred luminosity
- Disk models are too effectively thin for large values of a -- constrains surface density (and thus stress, [advection?])