# Accretion Disk Spectra

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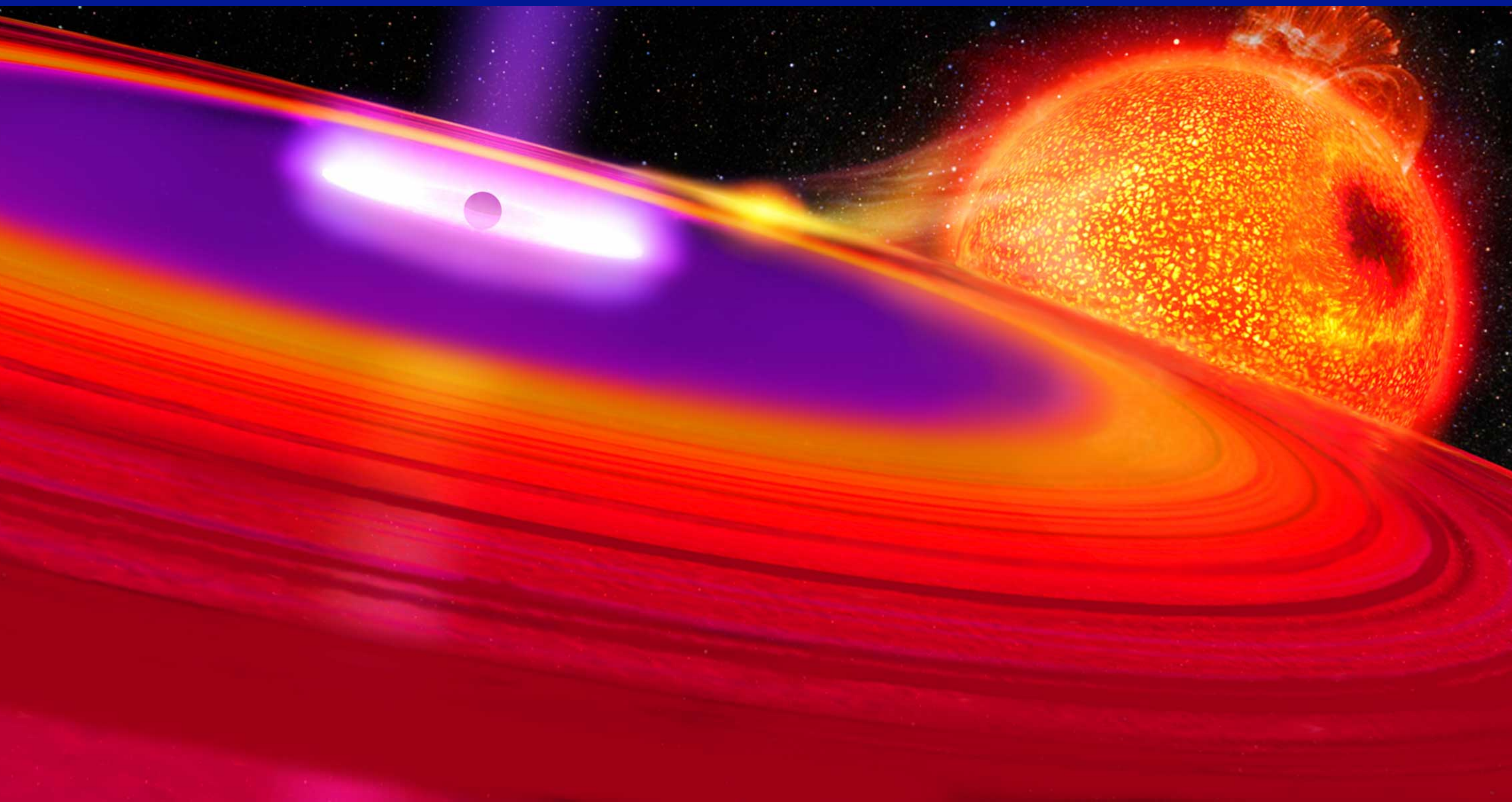
Black Hole Astrophysics: Tales of Power and Destruction, Winchester, UK, July 18, 2011



# Topics I will Discuss

1) Accretion Disk Spectral Models
   - Radial and Vertical Structure
   - Spectral Formation
   - Black Holes/General Relativity
2) Observational Applications
   - X-ray Binaries
   - Ultraluminous X-ray sources (ULXs)
   - Active Galactic Nuclei (AGNs)
3) Prospects for Future Work

# Important/Related Topics I Will Not Discuss

- ADAFS/Corona/Non-thermal hard X-rays
- Fe lines/Spectral lines
- Polarization
- Variability
- Winds/Jets/Outflows
- Dust/reprocessing
- Sgr A*

# Basic Accretion Disk Model

Amazingly, there is a simple self-consistent model for disk accretion which includes relatvistic effects: the relativistic, radiatively-efficient, thin $\alpha$-disk:
Shakura & Sunyaev (1973), Novikov &Thorne (1973)

Thin disk

H/R << 1
Constant accretion rate
Gravitational binding energy radiated locally

$$F = -H\tau_{R\phi} R \frac{\partial \Omega}{\partial R}$$

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

$\alpha$-disk

Need surface density $\Sigma$ (g/cm$^2$) as function of R

Computed via stress prescription: $\tau_{R\phi} = \alpha P$

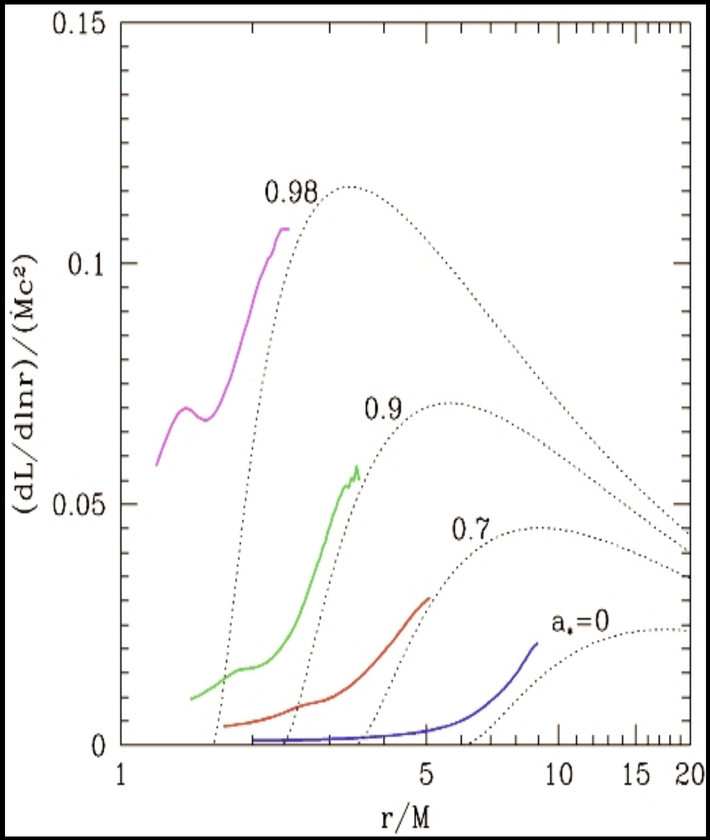
# Alternatives to Thin Disks

Slim disks: include effects of advection of energy and model flow into plunging region

Cons include reliance on $\alpha$/lack of magnetic fields, still fundamentally 1D

Global GRMHD simulations allow for first principles calculations of flow

Cons include lack of radiation/sensitivity to initial conditions/resolution



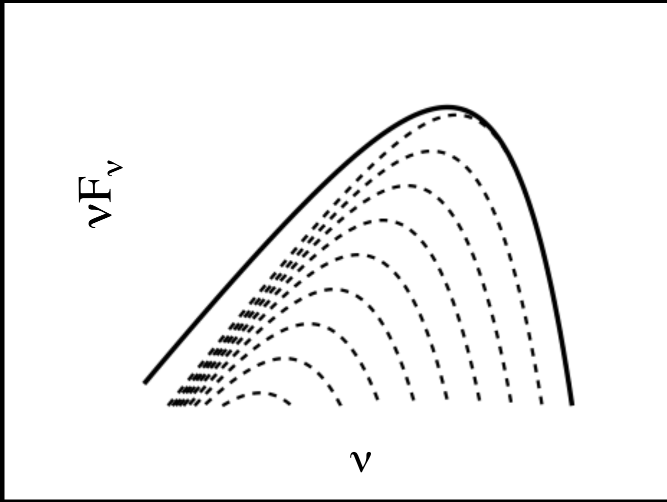

Penna et al., 2010

# Computing a Disk Spectrum

1) Must integrate from radii with different temperature: a multitemperature blackbody:

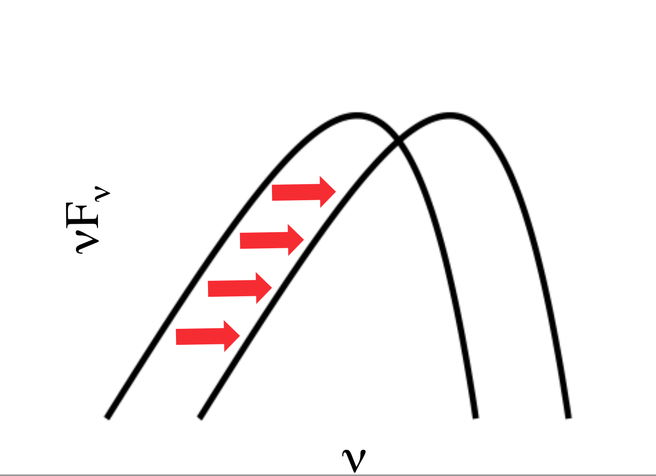
$$T \propto R^{-3/4}$$

Essentially the DISKBB model (Mitsuda et al. 1984)




2) Electron scattering and atomic opacity will cause deviations from blackbody: sometimes approximated as a "color-corrected" blackbody (Shimura & Takhara, 1995):

$$I_\nu = f^{-4} B_\nu(fT)$$



# Is it really that simple?

Self-consistent models of spectra at the disk surface must perform stellar atmospheres-like calculations:

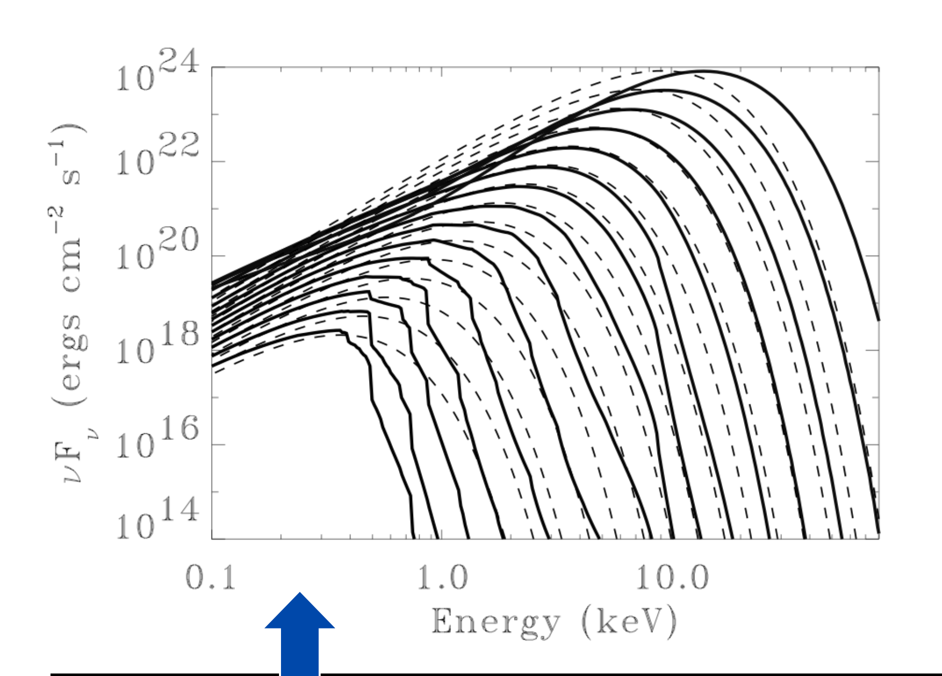
- Solve for hydrostatic equilibrium $$\frac{\partial P_{\rm tot}}{\partial z} = \rho \Omega^2 z$$
- Solve for radiative equilibrium $$\nabla \cdot F = \epsilon$$
- Solve equations of radiative transfer and statistical equilibrium (with Compton scattering, Bremsstrahlung, and atomic opacities)

Solving large system of coupled PDE's: typically involves iterative methods

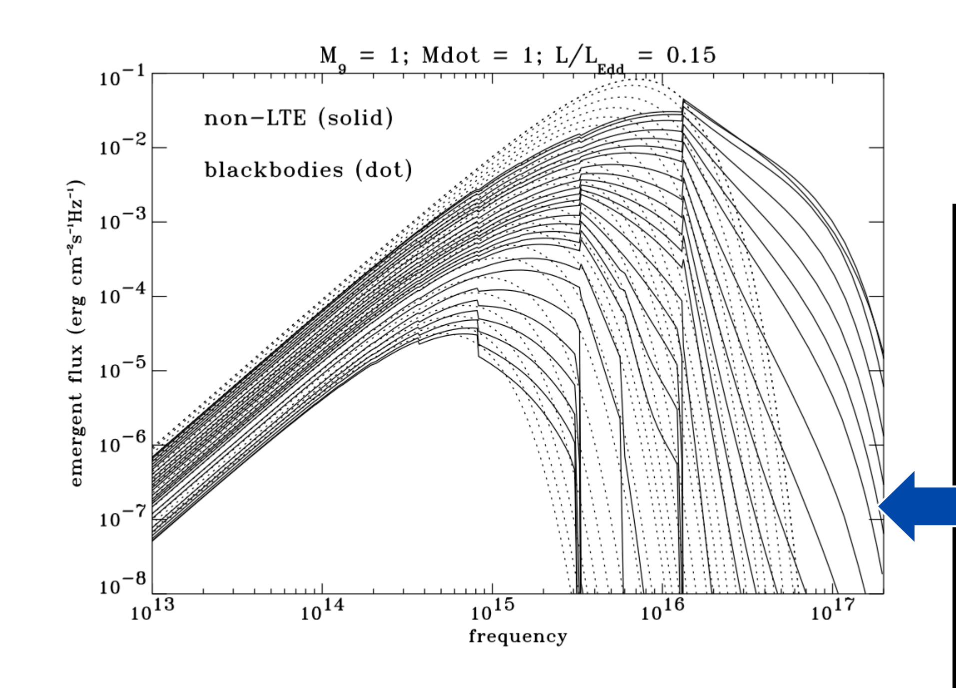
# Is it really that simple? (no)

Significant deviations from blackbody shape due to edges & electron scattering, even in X-ray binaries.

Best fit color correction (generally) increases with $T_{eff}$




X-ray binaries
(Davis & Hubeny, 2006)



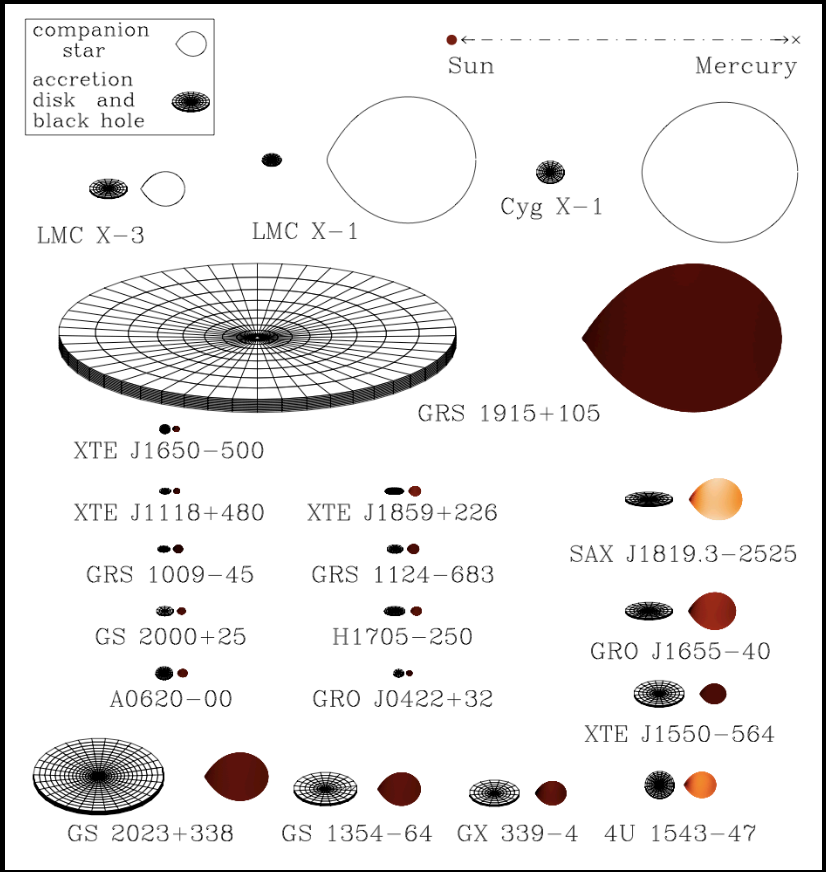

AGN (Hubeny et al. 2001)

# Black Holes

Astrophysical black holes are specified by only two parameters:
M: mass
$a_*$: spin ($cJ/GM^2$)

Mass is (relatively) easy. Reasonable constraints already exist:
X-ray binaries: dynamical models
AGN: M-$\sigma$ relation, BLR/viral estimates

Spin is hard because its effects are short range. Only a few other methods: Fe K$\alpha$ lines and (maybe) QPOs




Jerry Orosz

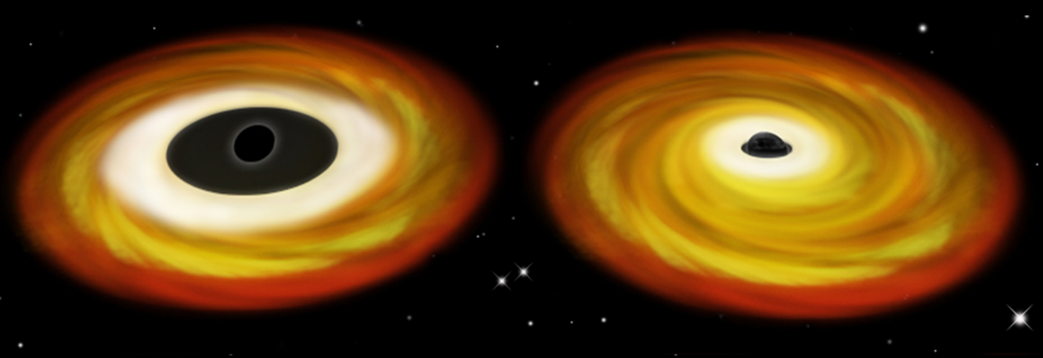
# General Relativity: Innermost Stable Circular Orbit

In GR, circular test particle orbits are not stable near a BH

Innermost stable circular orbit (ISCO) is determined by both M ($R_g = GM/c^2$) and $a_*$

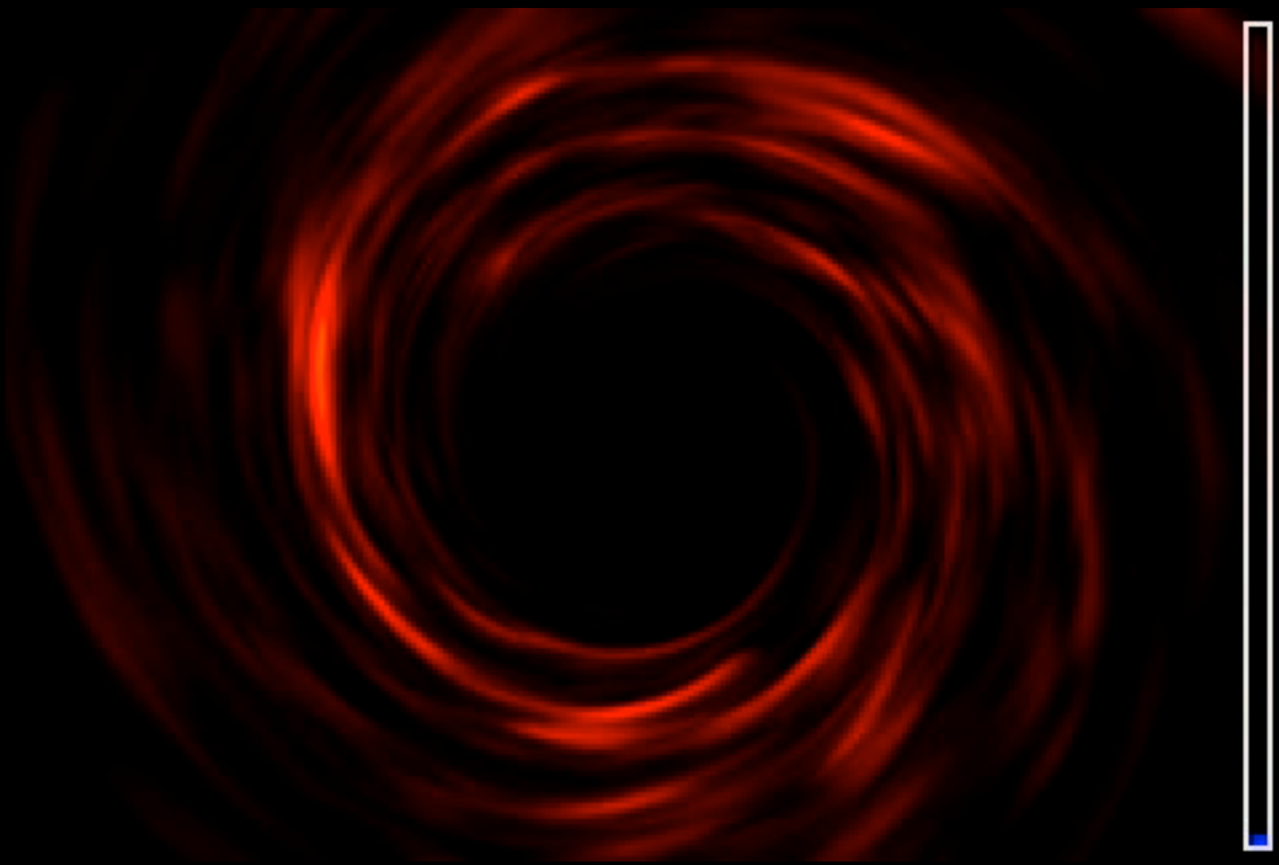
Assumption is that gas rapidly plunges into BH after crossing ISCO: $R_{isco} = R_{in}$

$a_* = 0$
$r_{isco} = 6$



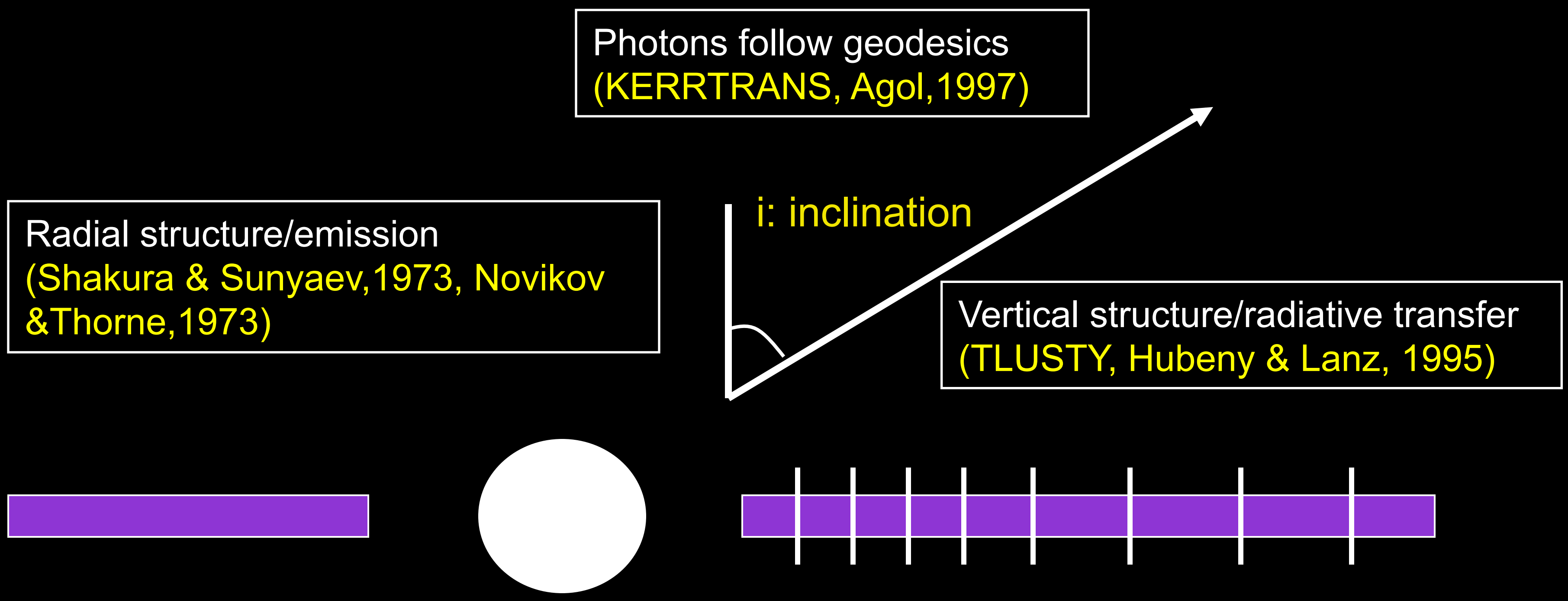
$a_* \sim 1$
$r_{isco} \sim 1$

# General Relativity: Light bending/beaming/lensing/redshift



Armitage & Reynolds, 2003

# Putting it All Together (e.g. BHSPEC/KERRBB)




**Thin ($\alpha$) Disk Model Parameters**

$M$: black hole mass

$L/L_{edd}$: luminosity/accretion rate

$a_*$: black hole spin

$\alpha$: stress parameter

**Annuli Parameters**

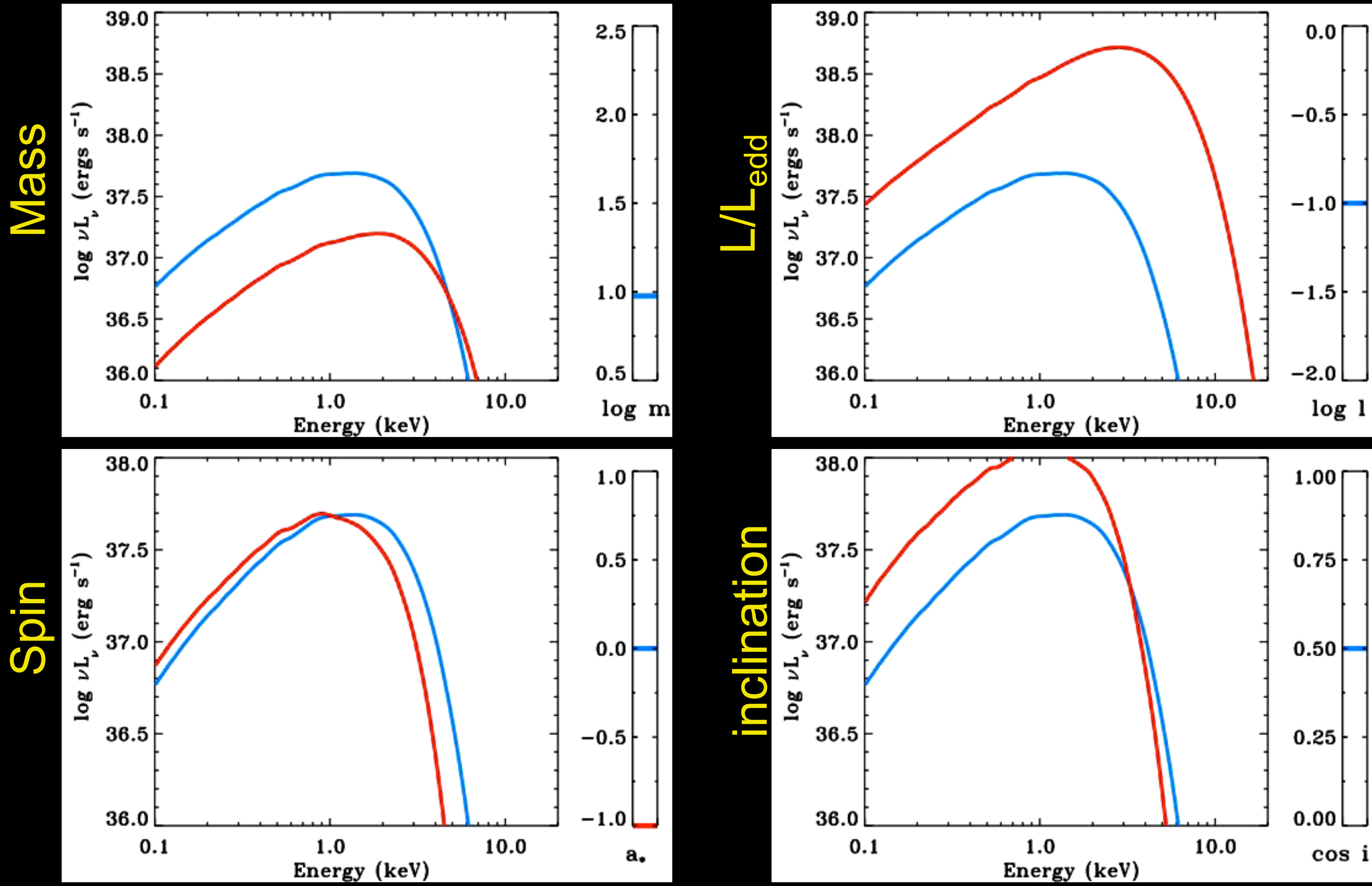
$\Sigma$: surface density

$Q$: gravity, $g=Qz$ ($Q \sim \Omega^2$)

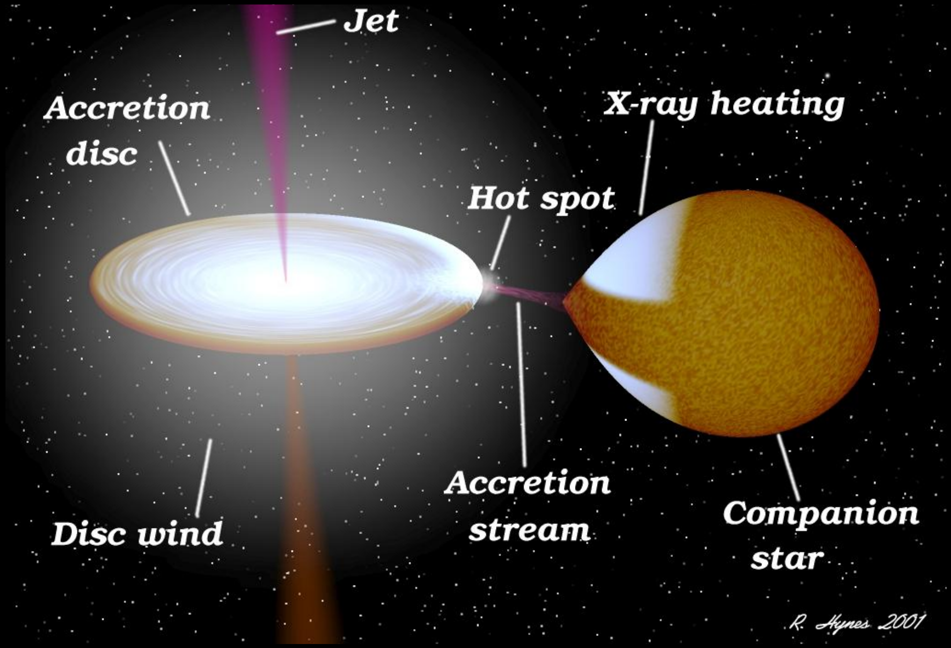
$T_{eff}$: effective temperature

(dissipation distribution, abundances, atomic data, etc.)

# Full Relativistic Disk Spectra (BHSPEC)



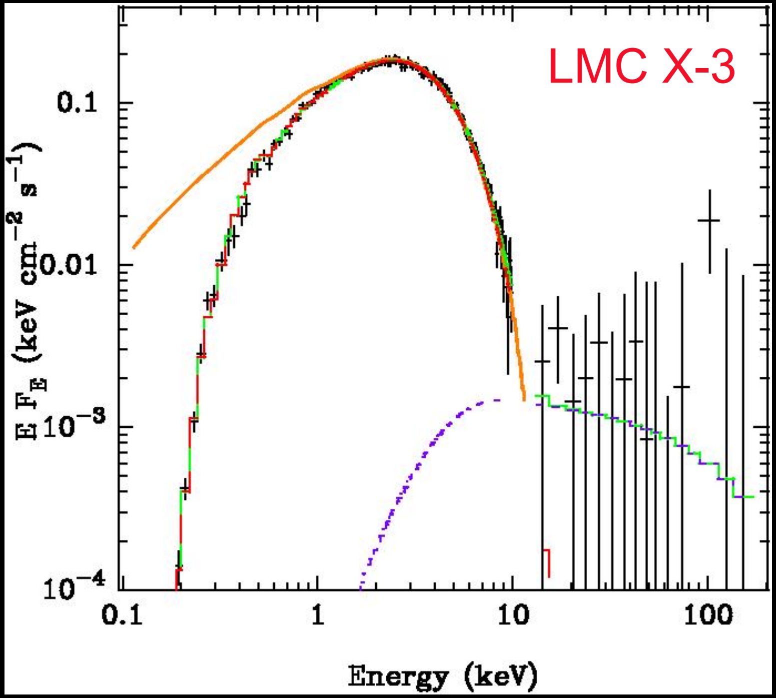
# X-ray Binaries



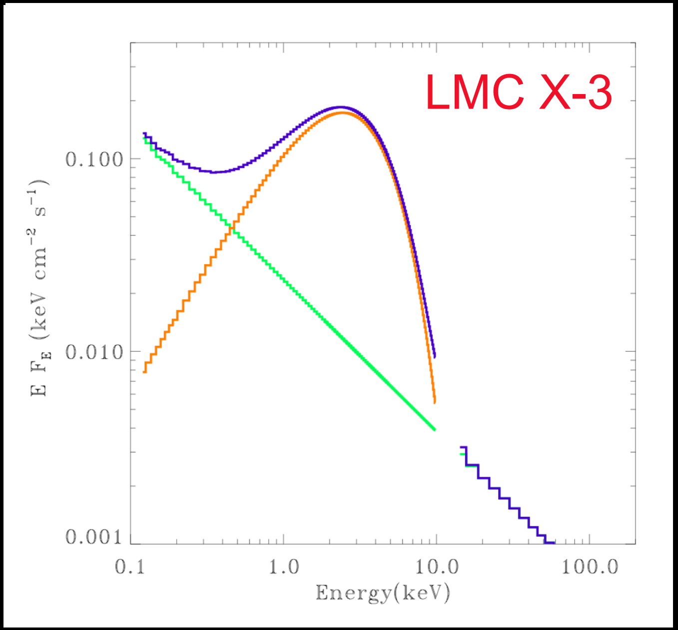

Rob Hynes

# "Broadband" Spectral Fitting

Relativistic models (BHSPEC and KERRBB) yield much more sensible fits to broadband data than simple multitemperature blackbody models




Davis et al. (2006)

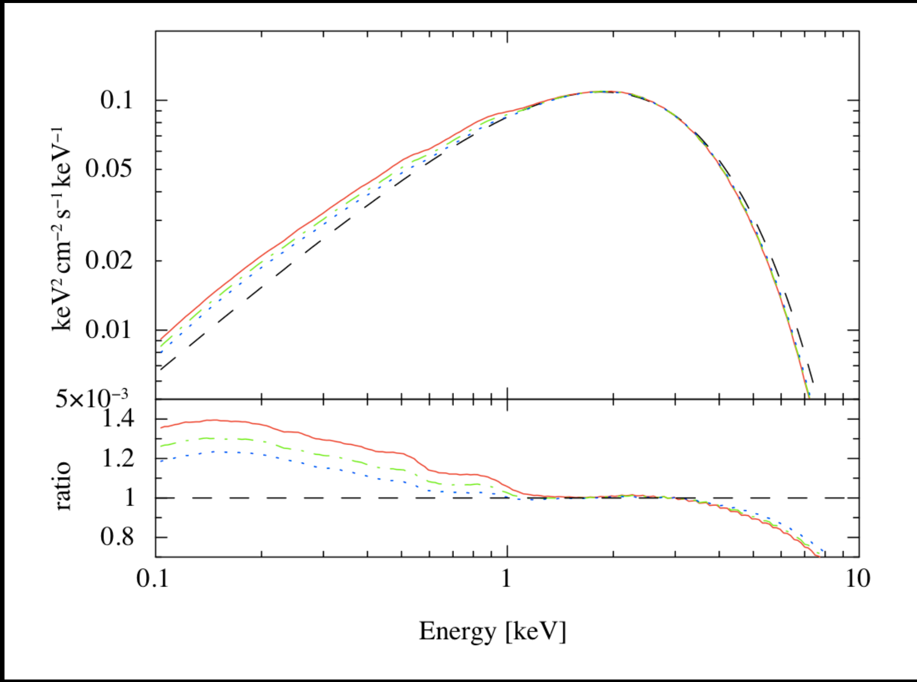



0.1-10 keV spectrum fit with just 3 parameters! $a_*$, $L/L_{edd}$, and $N_H$.

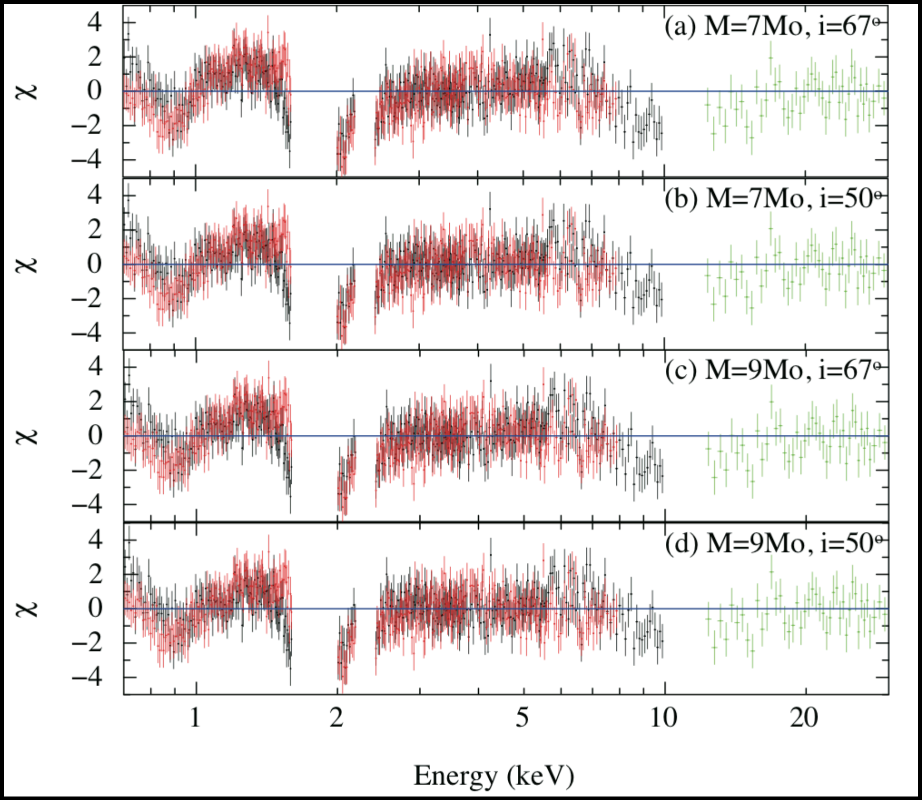
# "Broadband" Spectral Fitting

However, higher resolution (Suzaku) indicates there are some problems – edges in the models are NOT in the data!

Reminiscent of AGNs where Lyman edge is NEVER seen



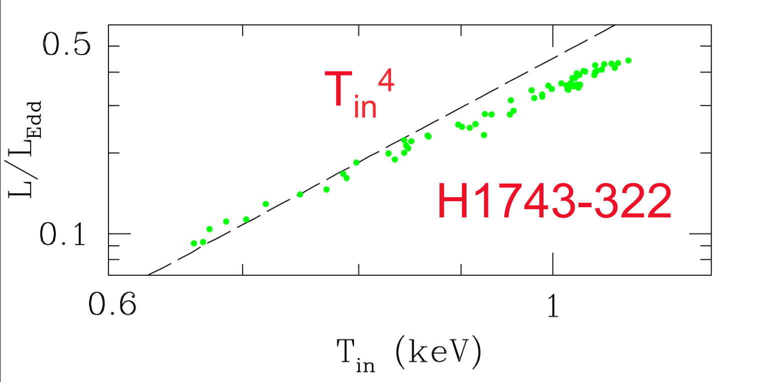

Kubota et al. (2010)



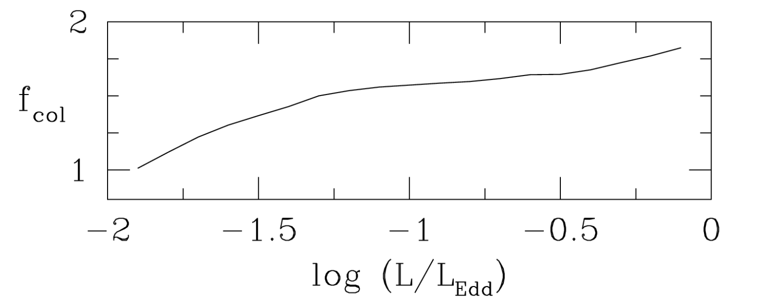

Kubota et al. (2010)

# Luminosity - Temperature Relation

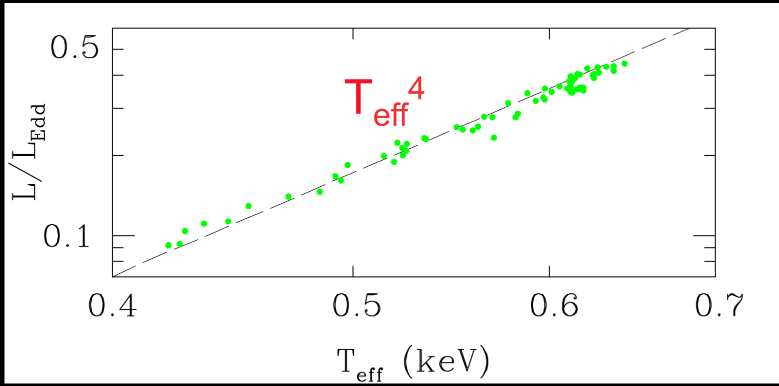
Using multitemperature blackbody one finds $L \sim T^4$, where $T = T_{in}$. Radius is nearly (but not exactly) constant




Shafee et al. (2006)



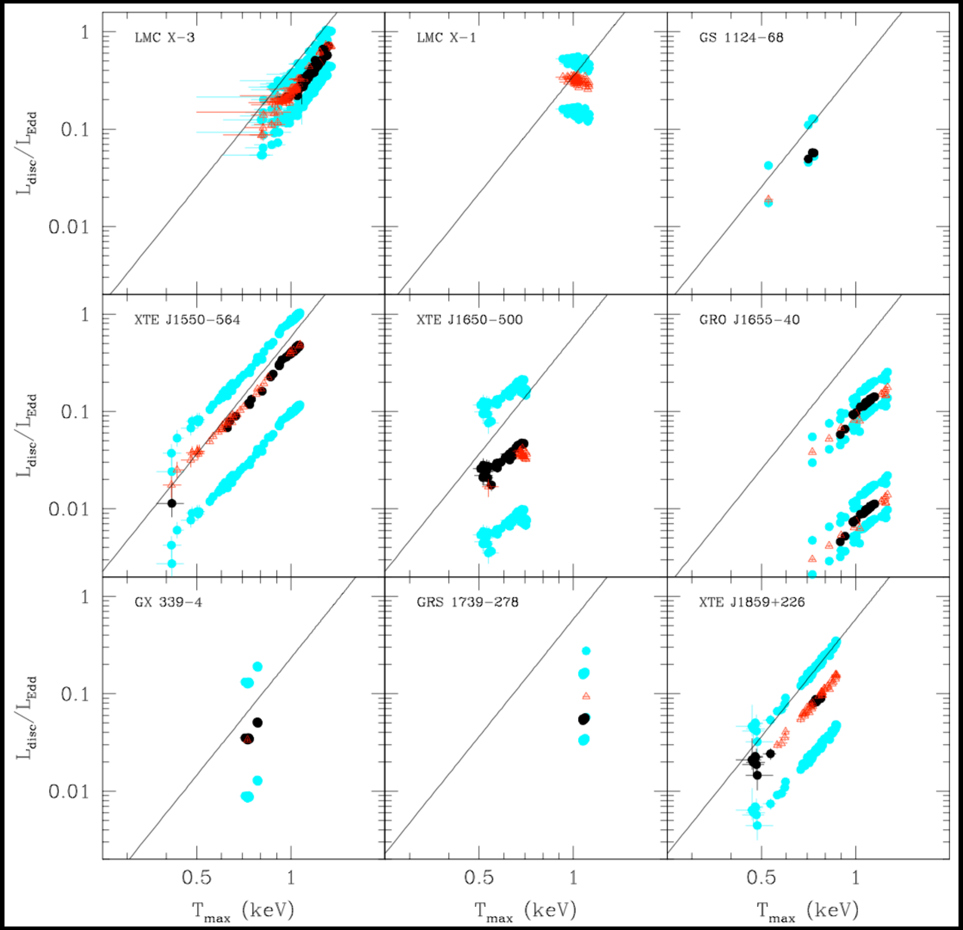

Use a color correction $f_{col}$ to "correct" the relations




Radius is now constant! Spectral hardening is due increasing ratio of electron scattering to absorption opacity as disks get hotter.

# Luminosity - Temperature Relation

A variety of $L - T$ relations are seen and NOT all are consistent with $f_{col}$ being a weakly increasing function of $L/Ledd$



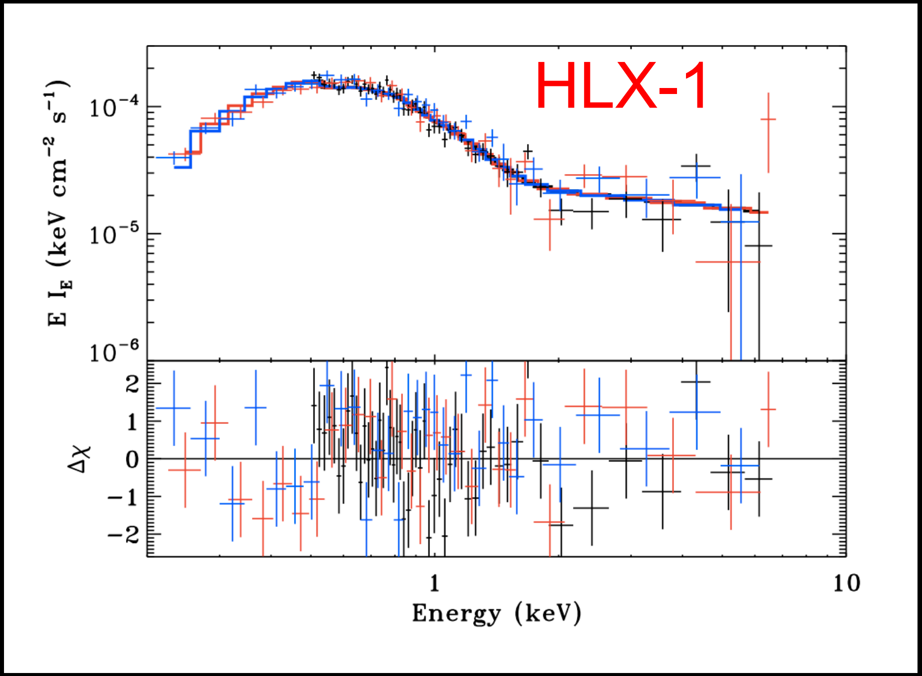

Gierlinski & Done (2004)

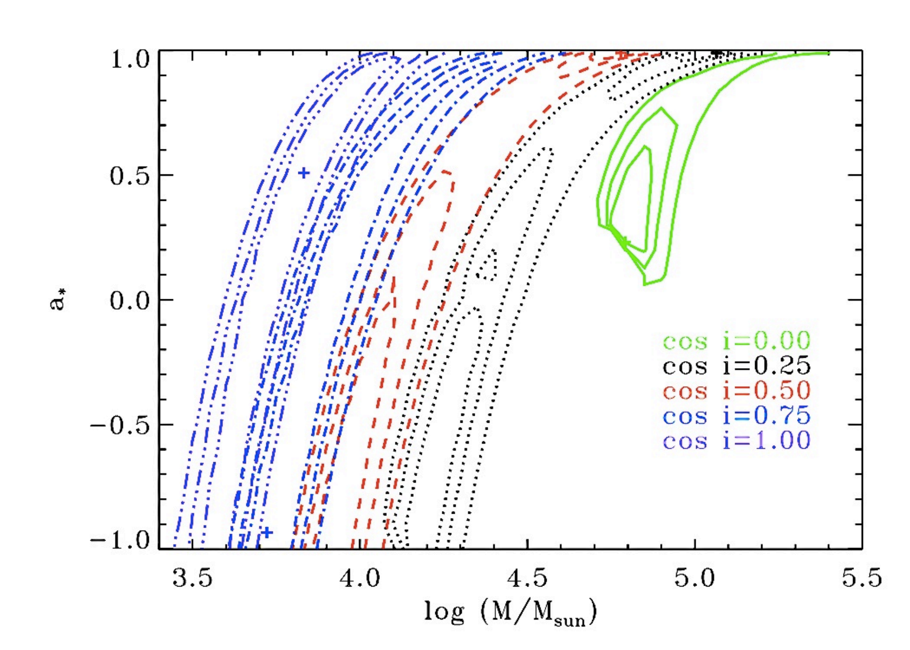
# Spin Estimates

| System | $a_*$ | Reference |
|---|---|---|
| GRO J1655-40 | 0.7 ± 0.05<br>~0.7 | Shafee et al. 2006<br>Davis et al. 2006 |
| 4U 1543-47 | 0.75 - 0.85 | Shafee et al. 2006 |
| LMC X-3 | < 0.25 | Davis et al. 2006 |
| XTE J1550-564 | 0-0.7<br>-0.11-0.71 (0.49 ± 0.20) | Davis et al. 2006<br>Steiner et al. 2010 |
| GRS 1915+105 | 0.98 - 1<br>~0.8 | McClintock et al. 2006<br>Middleton et al. 2006 |
| M33 X-7 | 0.84 ± 0.05 | Liu et al. 2007 |
| LMC X-1 | 0.92 (+0.05, -0.07) | Gou et al. 2009 |
| A0620--00 | 0.12 (+0.18, -0.20) | Gou et al. 2010 |
| Cygnus X-1 | 0.97-1 | Gou et al. 2011 |

# Models Can Fit (some) ULXs

Applications to ULX's somewhat limited:
- generally less well constrained (mass?)
- generally not in thermal disk state
- Hui & Krolik (2008) fit a handfull using BHSPEC models



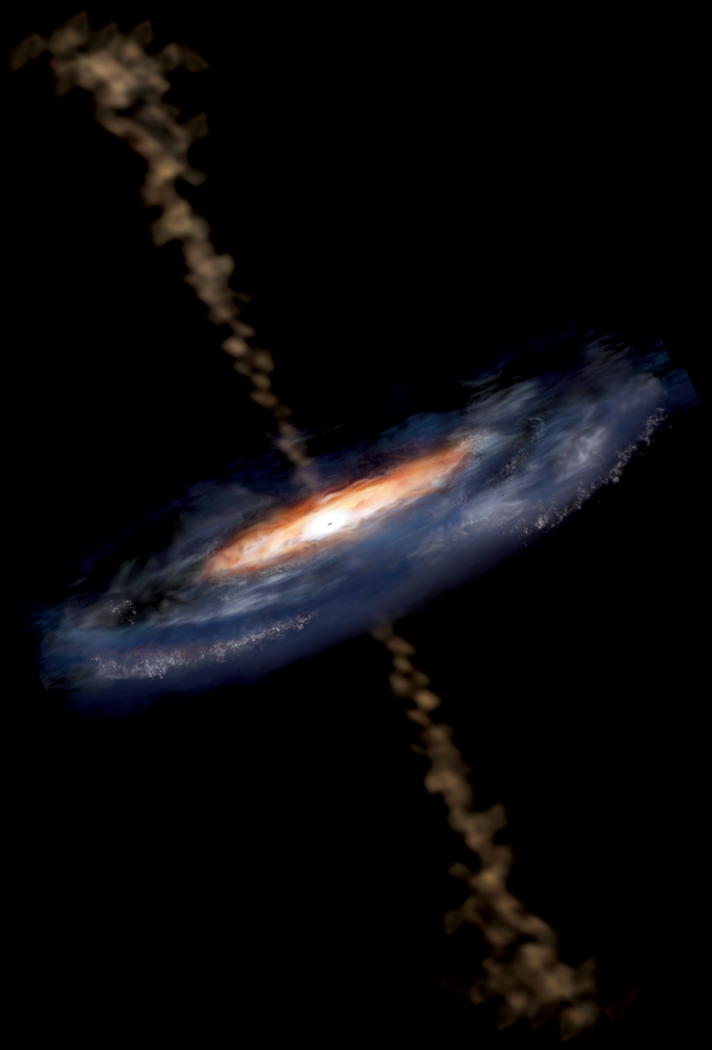




Davis et al. (2011)

HLX-1 in ESO 243-49 is a notable exception: $L > 10^{42}$ erg/s – strong candidate IMBH

Use spectral fitting to constrain mass (see talk by Natalie Webb)

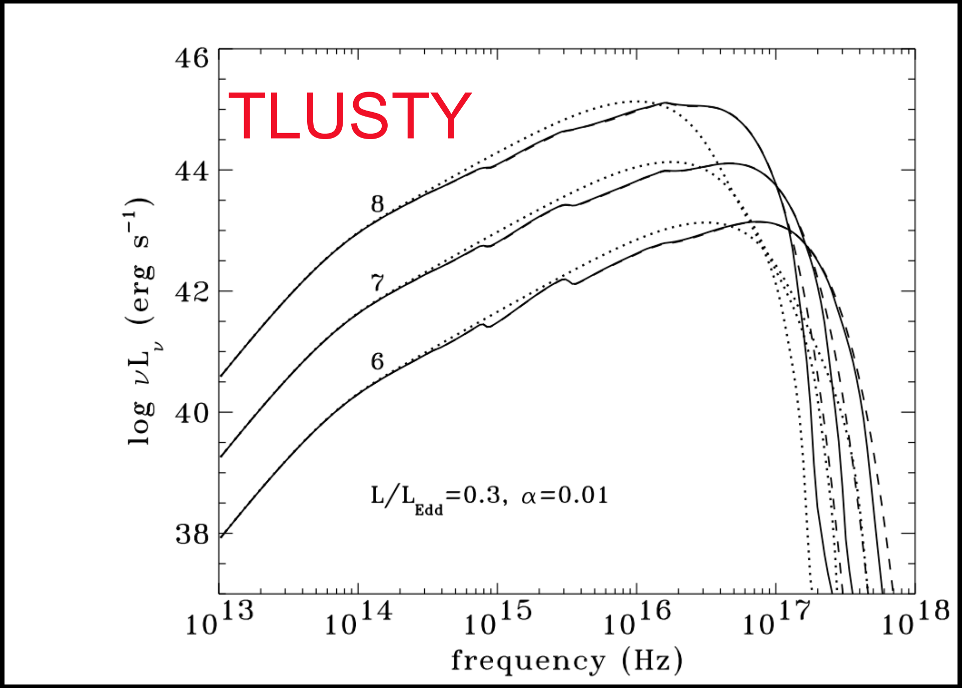
# Active Galactic Nulei



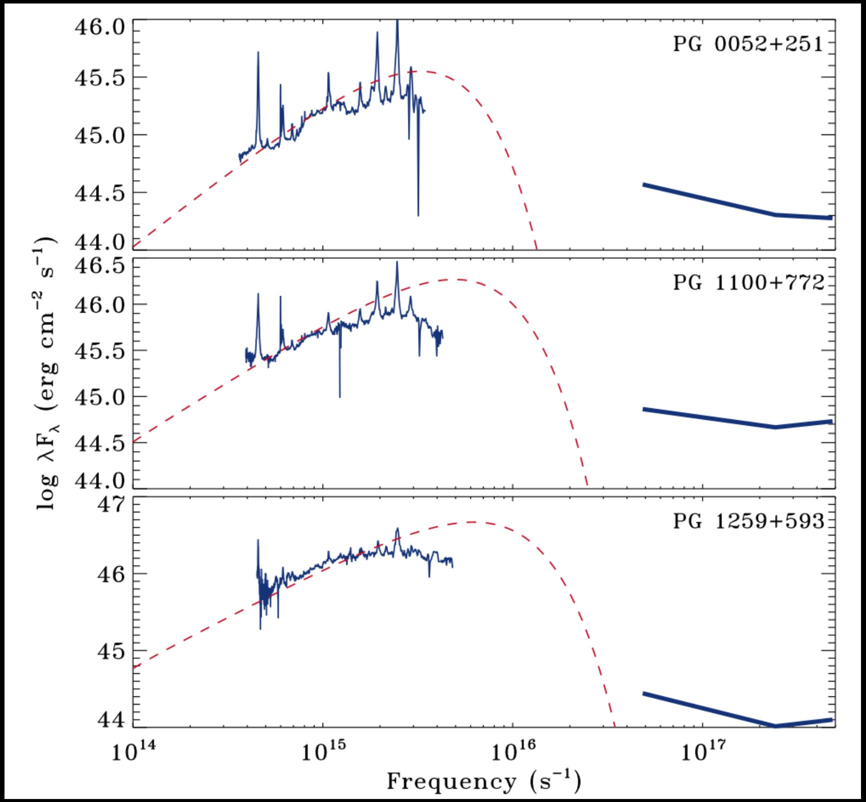
# Models (generally) Do Not Fit AGN

AGN generally poorly fit by disk models:

- UV slopes of real quasars are flatter
- Models do not predict X-ray emission
  (see talk by Chris Done)

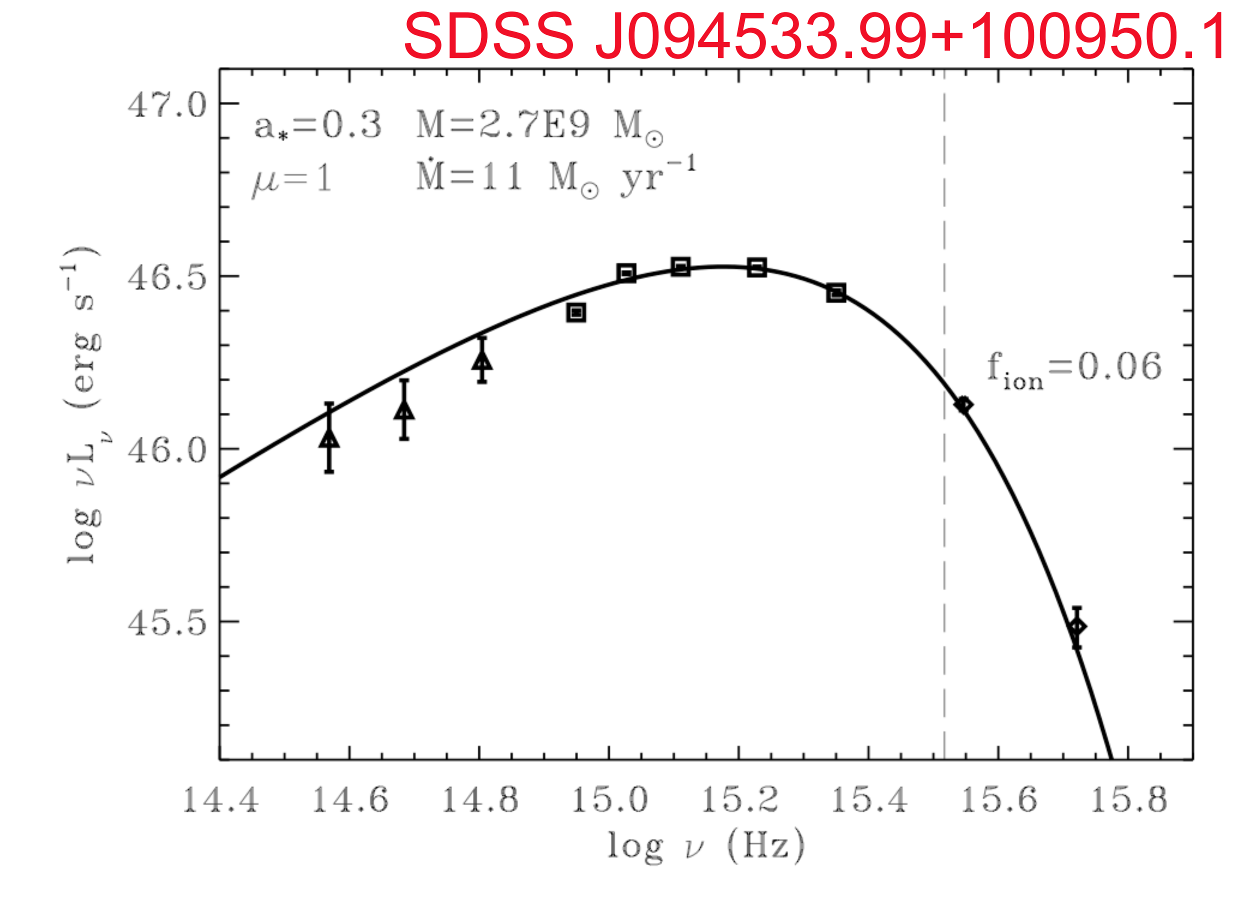



Hubeny et al. (2001)




Optical/Hubble/Fuse spectra -- Brotherton et al.
X-ray slopes -- Brandt et al.

# Possible exceptions?




Laor & Davis (2011)

Czerny et al. (2011) model AGN spectrum and find good fits and $a_* \sim 0.3$ with blackbody models. But Hubeny et al. models show edges which are too strong!

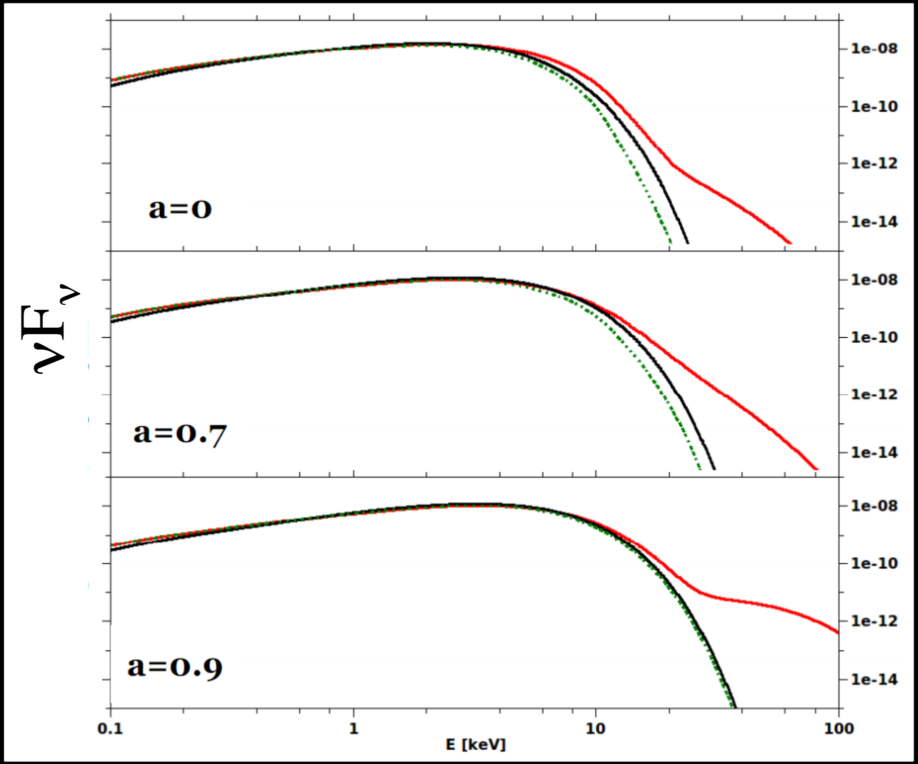
# Prospects/Goals for Future Work

- Fe lines from stellar atmosphere models
- Irradiation of disks (self irradiation or corona)
- Models effects of magnetic fields on vertical structure
- Time variability
- Understand spectral discrepancies in AGN
- Microlensing size discrepancies in AGN
- Emission from near or inside the ISCO
- Numerical simulations with radiative transfer

WORK IN PROGRESS!

# Emission from the Plunging Region

Many authors have considered the effects of emission from inside the ISCO assuming blackbody emission (e.g. Beckwith et al. 2008, Noble et al. 2009,2010,2011, Penna et al. 2010, Kulkarni et al. 2011)




Yucong Zhu is calculating the emission from plunging region using simulations and TLUSTY models

# Spectral Models from Radiative Transfer in Numerical Simulations

$f_{Edd}=P_{rad}/E_{rad}$