

ULTRA-LUMINOUS X-RAY  
SOURCES POWERED BY STELLAR-  
MASS BLACK HOLE ACCRETION

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# OUTLINE

- **WHAT ARE ULTRA-LUMINOUS X-RAY SOURCES (ULXs)**
- **WHY THEY ARE INTERESTING & OVERVIEW OF OBSERVATIONS AND THEORY**
- **BASIC IDEA OF OUR ULX MODEL**
- **FLOW STRUCTURE & RADIATION MECHANISMS**
- **SUMMARIZE**

# WHAT ARE ULXs?

**ULXs ARE EXTRAGALACTIC OFF-NUCLEAR BRIGHT X-RAY POINT SOURCES.**

**DISPLAY SHORT TERM (~ DAYS - WEEKS) VARIABILITY**



**RELATIVELY COMPACT IN COMPARISON TO SUPERNOVA REMNANTS**



**IMPLIES SOME TYPE OF X-RAY BINARY PHENOMENA**

**LOCATED IN BOTH SPIRAL AND ELLIPTICAL GALAXIES, BUT THE MOST LUMINOUS ULXs SEEM TO TRACK STAR FORMATION**

# WHY ARE ULXS INTERESTING?

NOT ALL OF THEM ARE INTERESTING. IN FACT, MOST OF THEM ARE NOT. HOWEVER, A SMALL FRACTION OF THEM ARE QUITE INTERESTING BECAUSE THEY ARE UNUSUALLY BRIGHT. BRIGHTEST ULXS ARE FOUND IN SPIRALS W/

$$L_x \geq 10^{40} \text{ erg s}^{-1}$$

FOR ~10-20 OR SO SOURCES ( $\sim 0.2 - 10 \text{ keV}$  )

AND, NOTE THAT:

$$L_{\text{EDD}} = \frac{4\pi GM_{bh}c}{\kappa_{es}} \simeq 10^{39} \left( \frac{M_{bh}}{10M_{\odot}} \right) \text{ erg s}^{-1}$$

# TWO UNCOMFORTABLE, YET UNAVOIDABLE EXPLANATIONS

I.E., IF WE ACCEPT THAT THEY ARE X-RAY BINARY PHENOMENA AND THAT THEY UN-BEAMED, THEN

1) ULXS ARE POWERED BY SUB-EDDINGTON ACCRETION ONTO INTERMEDIATE MASS BLACK HOLES ( $M_{bh} \sim 10^2 - 10^5 M_{\odot}$ ) : INTERESTING FROM AN ASTRONOMICAL PERSPECTIVE

2) ULXS ARE POWERED BY SUPER-EDDINGTON ACCRETION ONTO STELLAR MASS BLACK HOLES WITH ( $M_{bh} \sim 10^{1/2} - 10^{3/2} M_{\odot}$ ) : INTERESTING IN TERMS OF THE BASICS PHYSICS OF ACCRETION



EITHER WAY, ULXS ARE WORTH UNDERSTANDING

# THE TRAPPING PROBLEM

THE FLOW BECOMES  
"CRITICAL" WHEN

$$t_{\text{cool}} \sim r/v_r \sim t_{\text{visc}}$$

FOR RADIATIVELY  
EFFICIENT SHAKURA-  
SUNYAEV LIKE ACCRETION,  
THIS OCCURS WHEN

$$\dot{M} \sim \dot{M}_{\text{Edd}} = \frac{4\pi GM_{bh}}{c\kappa_{es}}$$

ABOVE THE EDDINGTON  
RATE, THE RADIATIVE  
EFFICIENCY GOES DOWN  
LIKE

$$\eta \propto \dot{M}^{-1} \text{ if } \dot{M} \geq \dot{M}_{\text{Edd}}$$

**A RESULT OF LOCAL  
DISSIPATION**

EDDINGTON - LIMITED TRAPPING

- RADIATIVE EFFICIENCY  $\eta \sim 2/R_{in}$
- FOR  $\dot{M} \sim \dot{M}_{\text{Edd}}$ ,  $R_{in} \sim R_{\text{TRAP}}$

- FOR  $\dot{M} \gg \dot{M}_{\text{Edd}}$ ,  $R_{in} \ll R_{\text{TRAP}}$ ;  $R_{\text{TRAP}} \sim (\frac{\dot{M}}{\dot{M}_{\text{Edd}}}) R_g$

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# REASONS FOR ADOPTING THE IMBH SCENARIO

1) BREAKING THE EDDINGTON LIMIT FOR A SUSTAINED AMOUNT OF TIME SEEMS DIFFICULT.

2) MANY OF THE LUMINOUS ULXS HAVE A COOL THERMAL DISK-LIKE SPECTRAL **COMPONENT** WITH

$$k_B T_d \sim 0.1 - 0.5 \text{keV}$$

COMPARE WITH

$$k_B T_d \sim 1 \text{keV} \quad \text{FOR A } \sim 10 M_\odot \text{ BH DISK @ } L_d = L_{\text{Edd}}$$

$$k_B T_d \sim 0.01 \text{keV} \quad \text{FOR A QUASAR DISK @ } L_d = L_{\text{Edd}}$$

IMPLIES LARGER EMITTING AREAS THAN NORMAL BHXRBs POWERED BY ACCRETION ONTO A STELLAR MASS BH AND A SMALLER EMITTING AREA THAN A QUASAR POWERED BY ACCRETION ONTO A SUPER-MASSIVE BH.

# ADOPTING THE INTERMEDIATE MASS BLACK HOLE SCENARIO

MORE SPECIFICALLY,

$$H_d \tau_{r\phi} \frac{d\Omega}{d \ln r} = F^+ \simeq \sigma T_{eff}^4$$

SHAKURA-SUNYAEV 1973  
PRESCRIPTION

$$\frac{GM_{bh} \dot{M}}{r^3} \sim \sigma T_{eff}^4 \Leftrightarrow L(r) \sim \frac{GM_{bh} \dot{M}}{r}$$

THE CHARACTERISTIC DISK TEMPERATURE SCALES LIKE  $T_d \propto M_{bh}^{-1/4}$  FOR A CONSTANT EDDINGTON RATIO SINCE  $r \propto M_{bh}$  FOR BH ACCRETION FLOWS. THEREFORE, INTERMEDIATE TEMPERATURES IMPLY INTERMEDIATE MASSES.

**BUT, LET'S TAKE A CLOSER LOOK AT THE OBSERVATIONS**

# SPECTRAL PROPERTIES OF HIGHLY STUDIED XMM AND CHANDRA ULXS WITH $L_X \geq 10^{40}$ erg s $^{-1}$

Source	Date	$k_B T_d$ (keV)	$\Gamma$	$F_{pl}/F_{total}$	$L_X$ ( $10^{40}$ erg s $^{-1}$ )	$N_H$ ( $10^{21}$ cm $^{-2}$ )	Reference
NGC 1313 X-1	2000 Oct 17	$0.23 \pm 0.02$	$1.76 \pm 0.07$	0.74 <sup>a</sup>	$0.6 \pm 0.1^a$	$3.1 \pm 0.3$	1
NGC 1313 X-2	2000 Oct 17	$0.16^{+0.16}_{-0.04}$	$2.3^{+0.2}_{-0.1}$	0.63 <sup>b</sup>	$0.66^{+0.18b}_{-0.20}$	$3^{+3}_{-1}$	2
M81 X-9	2002 Apr 10	$0.26^{+0.02}_{-0.05}$	$1.73 \pm 0.08$	0.85 <sup>a</sup>	$1.1^{+0.3a}_{-0.1}$	$2.3 \pm 0.3$	1
M81 X-9	2002 Apr 16	$0.21 \pm 0.04$	$1.86 \pm 0.06$	0.84 <sup>a</sup>	$1.3^{+0.3a}_{-0.2}$	$2.9 \pm 0.3$	1
NGC 4038/4039 X-11	2002 Jan 8	$0.15 \pm 0.02$	$1.9 \pm 0.2$	0.61 <sup>a</sup>	$2.1^{+0.7a}_{-0.1}$	$3.0^{+0.8}_{-1.8}$	3
NGC 4038/4039 X-16	2002 Jan 8	$0.19 \pm 0.05$	$1.4 \pm 0.2$	0.33 <sup>a</sup>	$1.6^{+0.4a}_{-0.1}$	$1.5 \pm 1.0$	3
NGC 4038/4039 X-44	2002 Jan 8	$0.15^{+0.02}_{-0.15}$	$2.2^{+0.1}_{-0.4}$	0.77 <sup>a</sup>	$1.0^{+1.3a}_{-0.2}$	$1.4^{+2.0}_{-0.4}$	3
NGC 4559 X-7	2003 May 27	$0.148 \pm 0.006$	$2.23^{+0.05}_{-0.04}$	0.63 <sup>c</sup>	2.2 <sup>c</sup>	$5.1^{+1.4}_{-1.3}$	4
NGC 4559 X-7	2001 Jun 4	$0.12 \pm 0.006$	$1.8 \pm 0.08$	0.69 <sup>c</sup>	1.9 <sup>c</sup>	$3.6^{+0.9}_{-1.1}$	4
NGC 4559 X-7	2002 Mar 14	$0.12 \pm 0.01$	$2.13 \pm 0.08$	0.54 <sup>c</sup>	3.2 <sup>c</sup>	$5.7^{+0.9}_{-1.1}$	4
M74 X-1	2001 Oct 19	$0.31 \pm 0.05$	$1.83^{+0.55e}_{-0.55}$	0.78 <sup>a</sup>	0.4 <sup>a</sup>	0.48	5
Holmberg II X-1	2002 Apr 10	$0.141^{+0.018}_{-0.015}$	$2.64^{+0.05}_{-0.05}$	0.83 <sup>d</sup>	2.0 <sup>a</sup>	$1.6^{+0.2}_{-0.1}$	6
Holmberg II X-1	2002 Apr 16	$0.128^{+0.022}_{-0.013}$	$2.40^{+0.07}_{-0.05}$	0.74 <sup>d</sup>	1.7 <sup>a</sup>	$1.4 \pm 0.3$	6
Holmberg II X-1	2002 Sep 18	$0.120^{+0.022}_{-0.017}$	$2.89^{+0.09}_{-0.08}$	0.69 <sup>d</sup>	0.5 <sup>a</sup>	$1.4^{+0.5}_{-0.4}$	6
Holmberg II X-1	2004 Apr 15	$0.20 \pm +0.02$	$2.64 \pm 0.03$	0.91 <sup>d</sup>	1.2 <sup>a</sup>	$1.66^{+0.10}_{-0.02}$	7
NGC 5204 X-1	2003 Jan 6	$0.21 \pm +0.03$	$1.97 \pm 0.07$	0.82 <sup>b</sup>	0.44 <sup>a</sup>	$0.78^{+0.17}_{-0.27}$	8
NGC 5204 X-1	2003 Apr 25	$0.21^{+0.04}_{-0.03}$	$2.09^{+0.12}_{-0.13}$	0.69 <sup>b</sup>	0.55 <sup>a</sup>	$1.22^{+0.34}_{-0.29}$	8
M101 XMM-1 (P13/H19)	2002 Jun 4	$0.30^{+0.04}_{-0.06}$	$1.41^{+0.25}_{-0.15}$	0.74 <sup>a</sup>	0.27 <sup>a</sup>	$0.67^{+0.41}_{-0.19}$	9
NGC 7771 X-2	2002 June 21	$0.16^{+0.12}_{-0.03}$	$1.67^{+0.27}_{-0.26}$	0.80 <sup>a</sup>	$3.86^{+0.1}_{-3.21}$ <sup>a</sup>	$3.18^{+4.49}_{-2.51}$	10

References. — (1) Miller et al. (2004a); (2) Miller et al. (2003); (3) Miller et al. (2004b); (4) Cropper et al. 2004; (5) Kruss et al. 2005; (6) Dewangan et al. 2004; (7) Goad et al. 2005; (8) Roberts et al. 2005; (9) Jenkins et al. 2004; (10) Jenkins et al. 2005

**ALL CONTAIN A COOL DISK COMPONENT  
HOWEVER, THE FRACTION OF POWER RELEASED IN THE  
DISK COMPONENT IS SUBDOMINANT WHEN COMPARED  
TO THE POWER LAW COMPONENT**

## TWO EXAMPLES OF EXTRAPOLATED SPECTRA

CLEARLY, THESE ARE NOT  
THERMAL EMITTERS

AVERAGE SPECTRAL INDEX  
OF

$$\langle \Gamma \rangle \sim 2$$

POWER-LAW COMPONENT,  
PRESUMABLY THE RESULT  
OF THERMAL  
COMPTONIZATION IS  
RESPONSIBLE FOR A  
FRACTION

$$f \sim 0.7 - 0.95$$

OF THE RADIATIVE ENERGY  
RELEASE

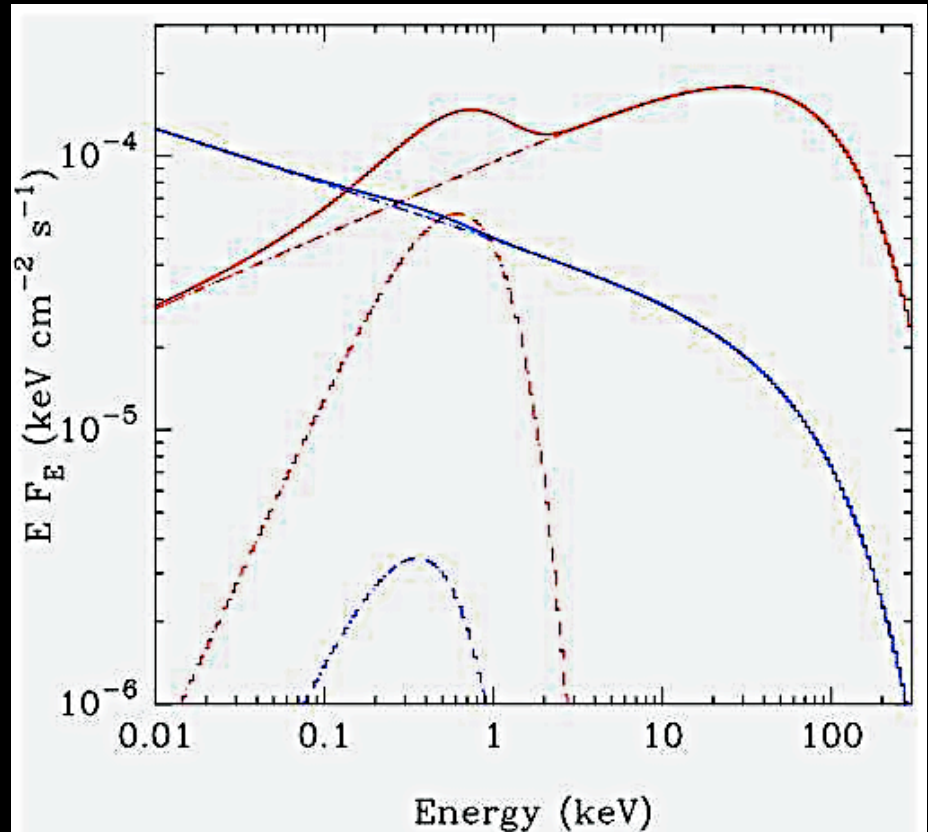


Fig. 1.— The best fit MCD + power-law model spectra are plotted for NGC 4038/4039 X-44 (blue) and M89 X-9 (2002 Apr 10; red). The curves represent the flux in the unabsorbed total model (solid), MCD component (dashed), and power-law component (dot-dashed) for the parameters listed in Table 1. Note that the models were fit with a power-law component over the 0.3-10 keV bands, but we have extrapolated the models assuming 100 keV cut-off to the power-law for the purpose of illustration. We have also rescaled the overall flux of M89 X-9 for illustrative purposes as well.

# EARLY SUMMARY

**MAJORITY OF THE RADIATIVE ENERGY RELEASE IN BRIGHT ULXs DOES NOT OCCUR LOCALLY**

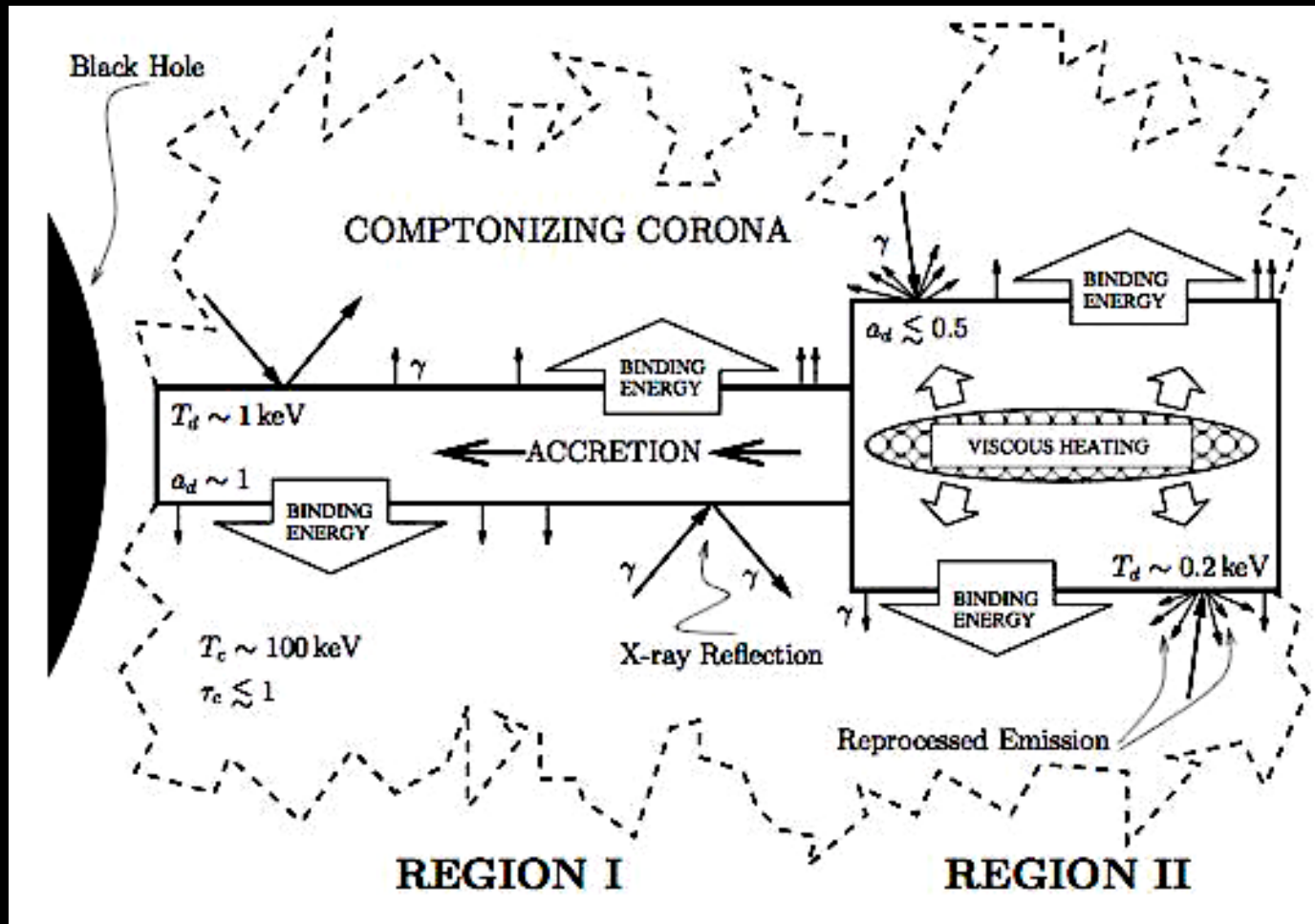
**OBSERVED THERMAL DISK EMISSION CANNOT BE USED TO CONSTRAIN BASIC PROPERTIES OF THE SYSTEM SUCH AS BH MASS IN A SIMPLE WAY -- BAD FOR IMBH MODELS**

**NON-LOCAL ENERGY RELEASE IMPLIES THAT BINDING ENERGY IS TRANSPORTED TO THE OBSERVER IN PART BY A MEANS OTHER THAN THOMSON SCATTERING-LIMITED RADIATIVE DIFFUSION**

**THUS THE TRAPPING OF BINDING ENERGY PROBLEM IS OVERCOME AND THE EDDINGTON LIMIT LOSES SOME (BUT NOT ALL) OF ITS MEANING.**

**PROVIDES MOTIVATION TO PURSUE MODELS OF BRIGHT ULXs POWERED BY TWO-PHASED RADIATIVELY EFFICIENT SUPER-EDDINGTON ACCRETION ONTO STELLAR MASS BHs.**

# PICTURE OF THE MODEL



MODEL HAS ADVANTAGE OF INVOKING NO NEW THEORETICAL IDEAS, JUST REALIZING THE APPLICABILITY OF PRE-EXISTING ONES THAT HAVE WITHSTOOD THE TEST OF TIME

# GETTING THE ENERGY OUT

ASSUME DISK STRUCTURE IS ALTERED BY CORONAL ENERGY INJECTION IN THE FOLLOWING WAY

$$F^+ \rightarrow F^+ (1 - f) \sim \frac{GM_{bh}\dot{M}}{r^3} (1 - f) \sim \sigma T_{eff}^4$$

AND ALSO ASSUME THAT EVERYTHING ELSE IS THE SAME:

$$\tau_{r\phi} \sim \alpha P ; P \sim P_{rad} ; F^- \propto P_{rad}/\tau_d$$

THE SOUND CROSSING TIME,  $t_s \sim H_d/c_s$ , IS A GOOD LOWER LIMIT FOR THE TIMESCALE OF REMOVING RANDOMIZED BINDING ENERGY, AND SHOULD BE COMPARED TO VISCOUS OR ADVECTION TIMESCALE

$$t_{adv} \sim R/v_r$$

## ...GETTING THE ENERGY OUT

THE RATIO BETWEEN THE TWO MUST BE < 1

$$t_{adv}/t_s < \frac{\tilde{r}^{1/2} \tau_d}{\dot{m}} \sim \frac{\tilde{r}^2}{\alpha \dot{m}^2 (1-f)^2}$$

WHICH IS ~ 5 FOR

$$\alpha \sim 0.1; \tilde{r} \sim 12; \dot{m} \sim 175; f \sim 0.9$$

PERHAPS MAGNETIC BOUYANCY (RESULTING FROM MRI TURBULENCE) OR WAVES OF SOME SORT CAN TRANSPORT RANDOMIZED BINDING ENERGY AT THIS RATE. THESE IDEAS ARE OLD AND COME FROM OBSERVATIONS OF THE CHROMOSPHERE AND CORONA OF THE SUN. **BUT, NOBODY REALLY KNOWS WHAT THE MECHANISM ACTUALLY IS.** WE CAN CONCLUDE HOWEVER, THAT SOME MECHANISM FOR NON-LOCAL DISSIPATION IS AT WORK

# **MAINTAINING A HIGH RADIATIVE EFFICIENCY: LACK OF WIND POWER**

**TWO REASONS WHY MOST OF THE ACCRETION POWER MAY  
NOT BE CARRIED AWAY IN A WIND**

**1) COMPTONIZING CORONA DO NOT TRANSFER RADIATIVE  
POWER INTO MECHANICAL POWER VERY WELL BECAUSE**

**A) OPTICALLY THIN -- RADIATION AND MATTER ARE  
NOT HIGHLY MECHANICALLY COUPLED**

**B) EVERY TIME A PHOTON ATTEMPTS DONATE SOME  
MOMENTUM TO AN ELECTRON, IT ON AVERAGE TAKES  
SOME ENERGY FROM IT**

**C) RELATIVISTIC ABERRATION EFFECT ENHANCES  
COMPTON DRAG FROM SIDE-SCATTERED RADIATION**

**2) HIERARCHY OF STRESSES/CONFINEMENT**

**A) PRESSURE IN CORONA IS SMALL IN COMPARISON  
TO THE MECHANICAL STRESSES AT LARGE DEPTH, EVEN  
IF NEARLY ALL OF THE BINDING ENERGY IS RELEASED  
THERE**

**B) FOR EXAMPLE, CONSIDER THE SUN.**

# SPECTRAL FORMATION: $\Gamma$ , $T_c$ , $\tau_c$ , $a_d$

AS USUAL, ASSUME THAT THERMAL COMPTONIZATION IS THE CORONAL EMISSION MECHANISM

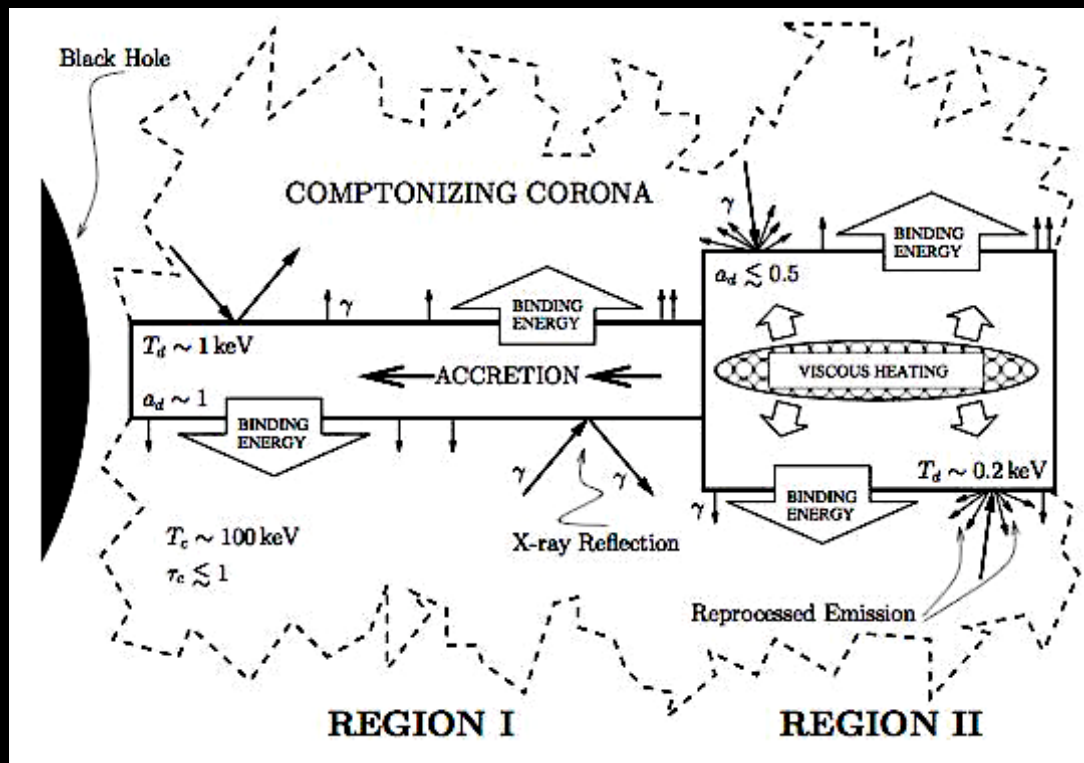
CAN REPRODUCE DATA IF REGION I EXTENDS OUT TO AT LEAST

$$\tilde{r} \sim 100$$

FOR PARAMETERS

$$\Gamma; T_c; \tau_c; a_d \sim 2; 100\text{keV}; 1; 1$$

ALBEDO IS THE BIG THE ISSUE. IF THERE IS TOO MUCH ABSORPTION THEN  $f < 1/2$  AND THIS MODEL WOULD NOT BE ABLE TO REPRODUCE THE DATA.



# ALBEDO/PHOTO-IONIZATION BALANCE

FROM DETAILED BALANCE (for  $f \sim 0.9$ ;  $\dot{m} \sim 10 \dot{m}_{Edd}$ ;  $\tilde{r} \sim 20$ )

$$n_i \int_{\nu_0}^{\infty} \frac{F_\nu}{h\nu} d\nu = n_e n_{i+1} \alpha_R(T) \longrightarrow \frac{n_{i+1}}{n_i} \sim 10^5 \text{ near the BH}$$

DEFINE  $\epsilon \equiv \kappa_{abs}/\kappa_T \sim \frac{n_i A_Z \sigma_0}{n_{i+1} \sigma_T} \sim 5 \cdot 10^{-4} \left( \frac{A_Z}{5 \cdot 10^{-5}} \right)$

THEN IN THE TWO-STREAM APPROXIMATION,

$$a_d \simeq \frac{1 - \epsilon^{1/2}}{1 + \epsilon^{1/2}} \simeq \frac{1 - 0.024}{1 + 0.024} \simeq 0.953$$

THE INNER-REGIONS SEEM TO BE A GOOD REFLECTOR OF  
CORONAL X-RAYS

# SUMMARY

CORONAL ENERGIZATION RESULTING FROM THE NON-LOCAL DISSIPATION OF BINDING ENERGY IS REQUIRED IN ORDER TO CIRCUMVENT THE TRAPPING PROBLEM FOR A SUPER-EDDINGTON ACCRETION

SEDS OF THE BRIGHT END OF THE ULX DISTRIBUTION ARE DOMINATED BY HARD POWER-LAW CORONAL EMISSION

THIS IMPLIES THAT AN INTERMEDIATE MASS BLACK ACCRETION IS NOT REQUIRED IN ORDER TO EXPLAIN ULX PHENOMENA -- STELLAR MASS BH ARE SUFFICIENT

A CORONAL-DOMINATED ACCRETION FLOW MODEL CAN REPRODUCE THE SEDS OF ULXS WHILE MAINTAINING A HIGH RADIATIVE EFFICIENCY