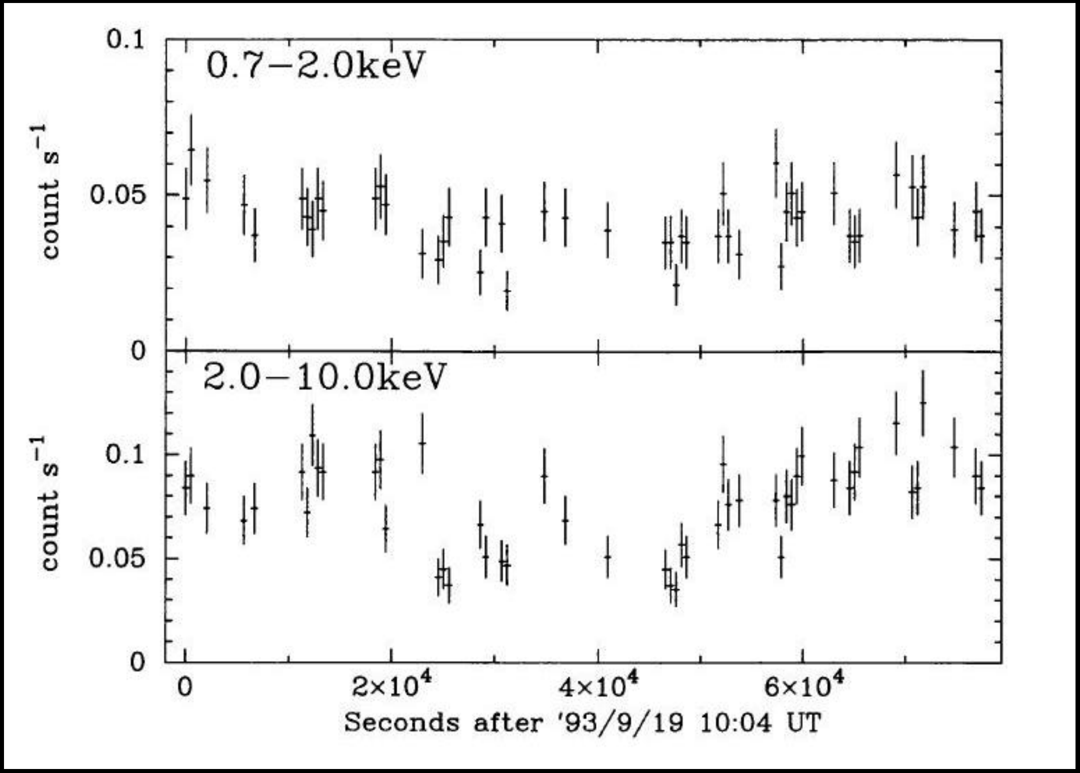
Accretion Disk Spectra of the Ultra-luminous X-ray Sources in Nearby Spiral Galaxies and Galactic superluminal jet sources

Ken Ebisawa, Piotr Zycki, Aya Kubota,
T. Mizuno, K. Watarai

Ultra-luminous X-ray Sources (ULX)

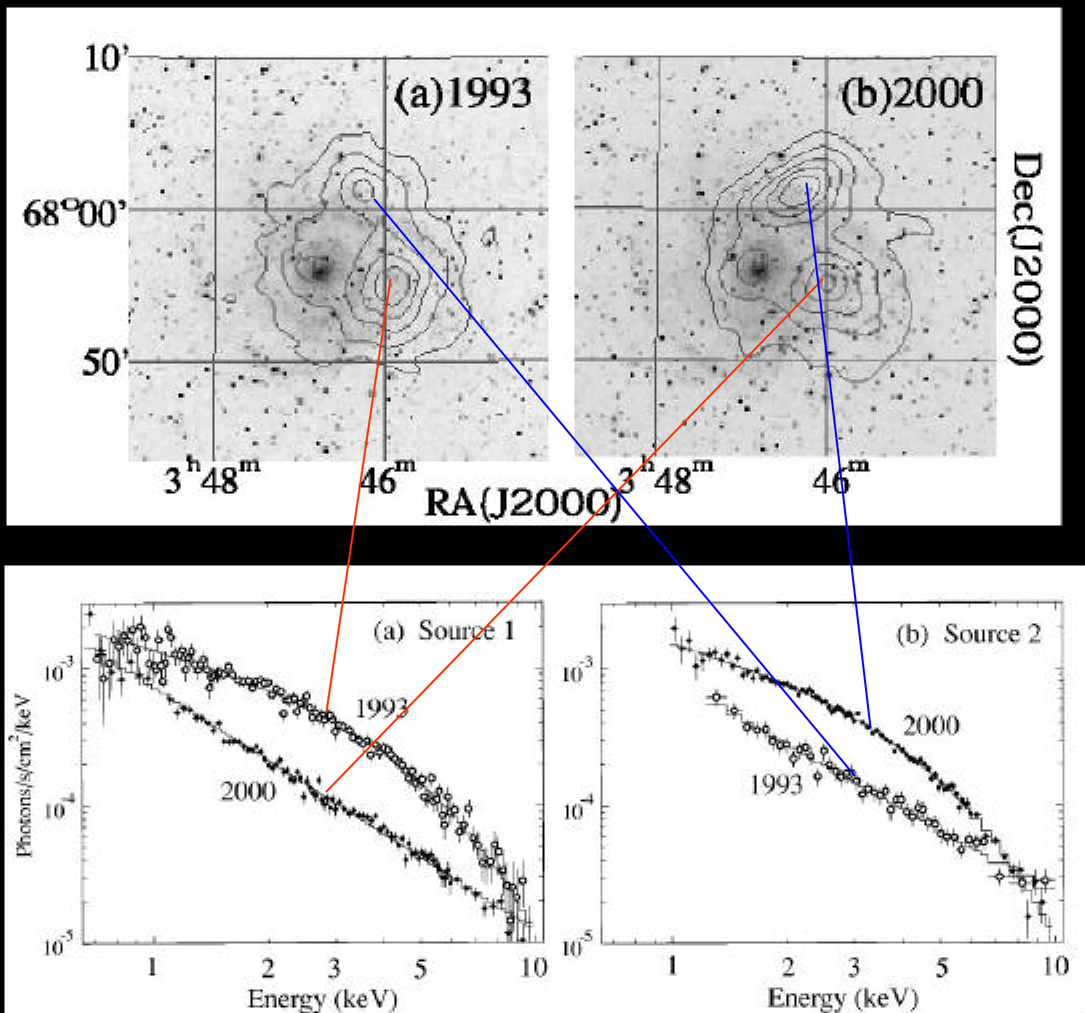
- Discovered with Einstein in nearby spiral Galaxies (e.g., Fabbiano 1988)
- L_X(0.5-10 keV)~10^{39}-10^{40} erg s^{-1}
- Too bright for X-ray binaries, too dim for AGN
- Most sources are located off-center of the Galaxy (Colbert and Mushotzky 1999)
- >100 $M_\odot$ not to exceed the Eddington limits?

Characteristics of ULX



- Significant time variation (Source1 in IC342; Okada et al. 1998)
- Compact object in nature

Characteristics of ULX



- High-low transition? (Source1 and 2 in IC342; Kubota et al. 2001)
- Orbital modulation (?) from Source 2 (Sugiho et al. 2001) , from a ULX in Circinus galaxy (Bauer et al. 2001)
- Similar to Galactic black hole candidates

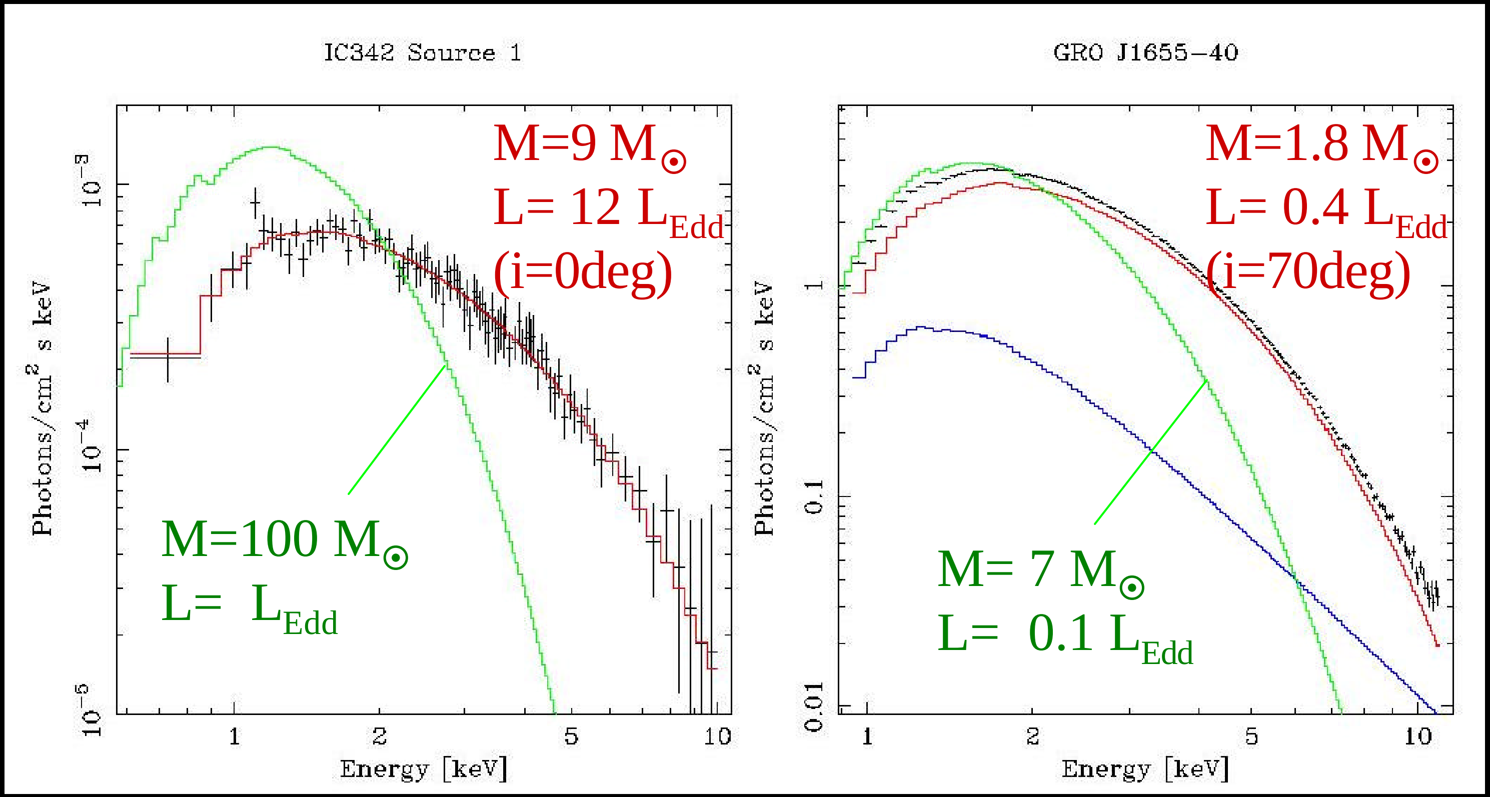
"Too-hot disk" problem in ULX and superluminal jet sources

- ULX energy spectra
  - Thermal spectrum, like standard optically thick accretion disk (no advection, $T_{eff}(r) \propto r^{-0.75}$)
  - Disk temperature too high for given luminosity and mass, assuming Schwarzschild black hole ($R_{in} = 3\ R_s$) (Okada et al. 1998; Makishima et al. 2000)
- Same problem in Galactic superluminal jet sources GRS1915+105 and GRO J1655-40 (Zhang, Cui and Chen 1997)

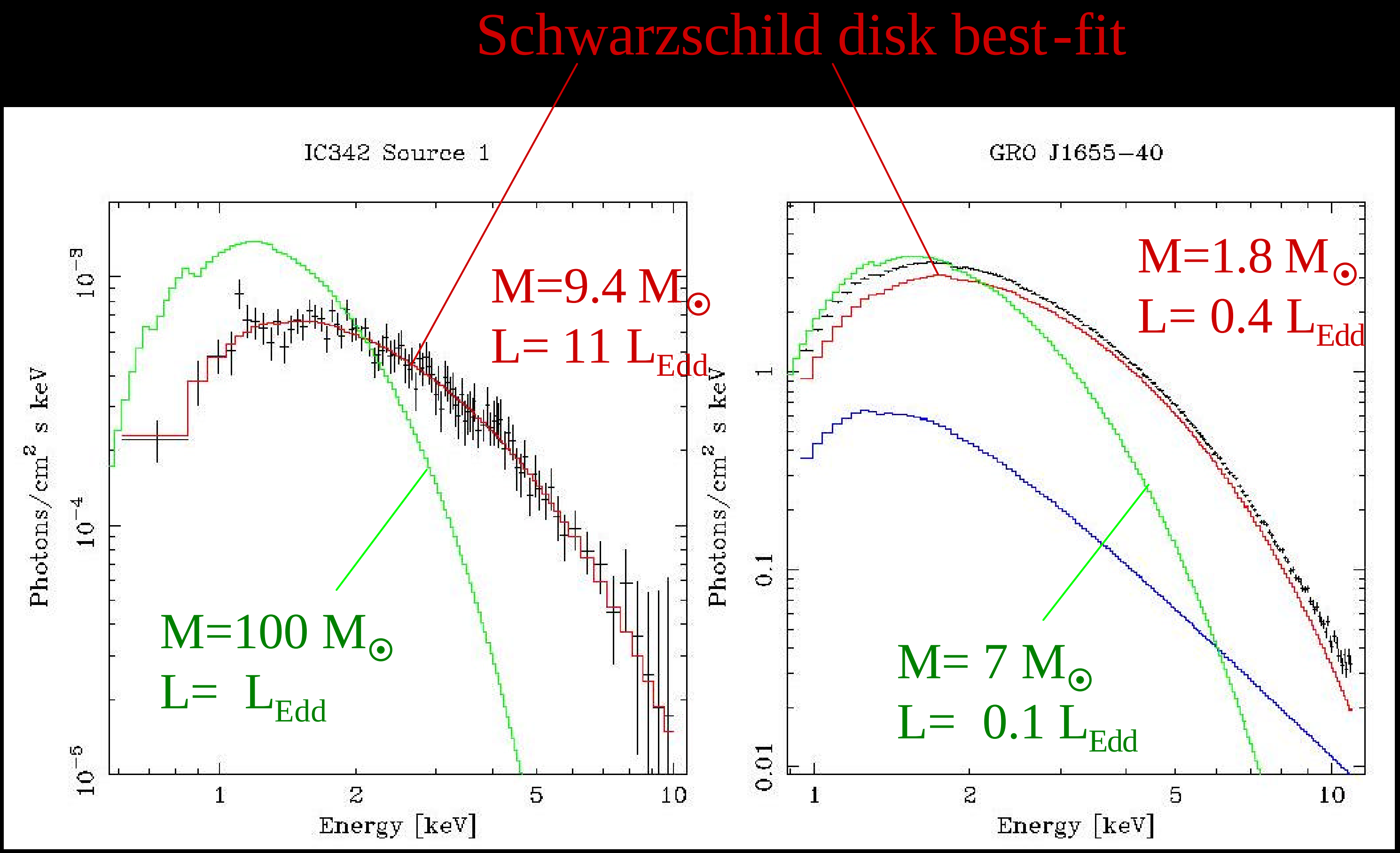
"Too-hot disk" problem in ULX and superluminal jet sources

Disk color temperature for Schwarzschild black hole

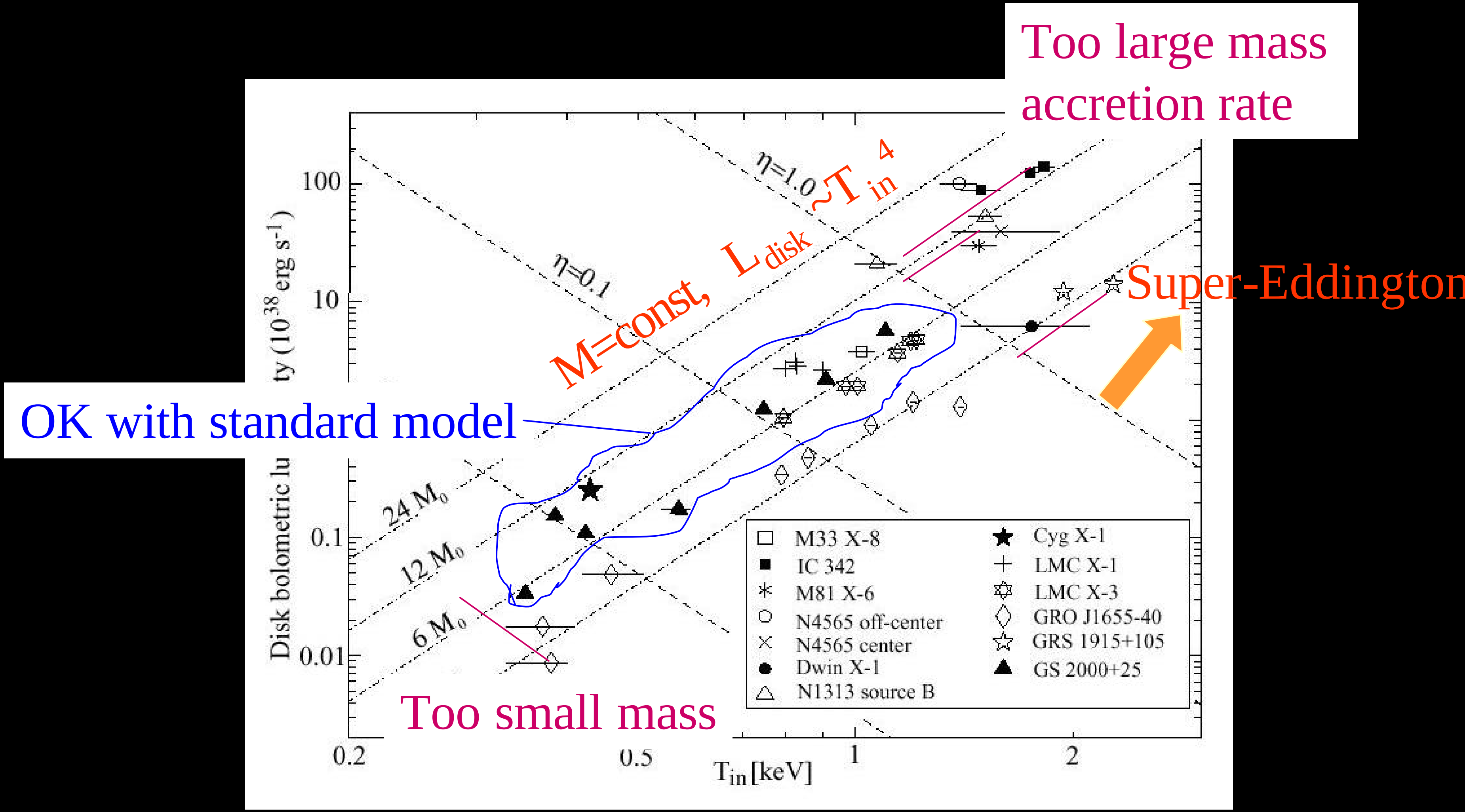
$$T_{col} \sim 1.3\ \mathrm{keV}\ ((T_{col}/T_{eff})/1.7)\ (\dot{M}/\dot{M}_{Edd})^{1/4}\ (M/7M_{\odot})^{-1/4}$$



Either too large mass accretion rates
(super-Eddington luminosity) or too small mass required



- Too hot accretion disks in ULX and superluminal jet sources
- To explain the observation, you need either too large mass accretion rate or too small mass, as long as standard disk around Schwarzschild black hole is assumed

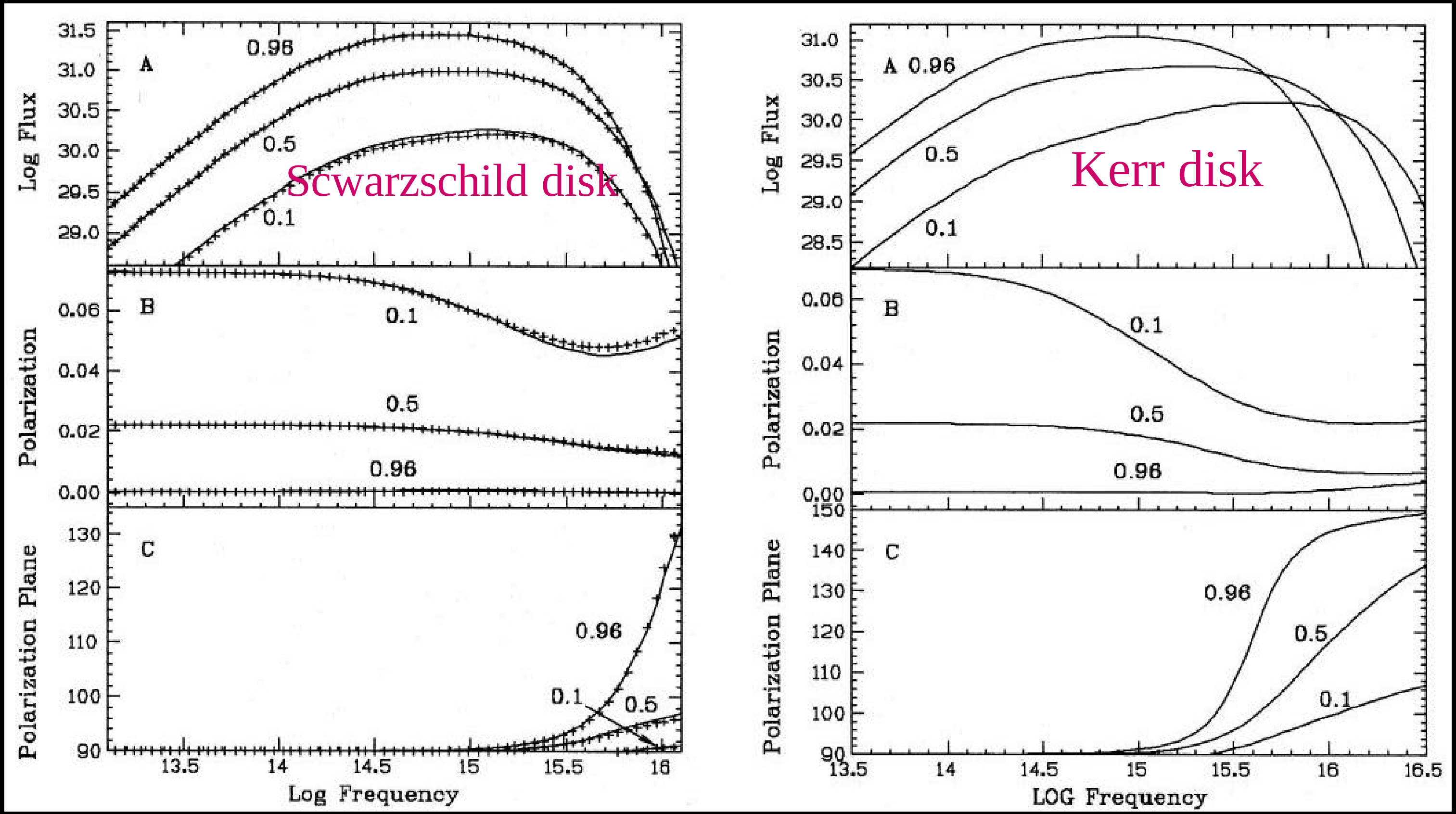


- Makishima et al. (2000)

How to explain the "too-hot" accretion disk?

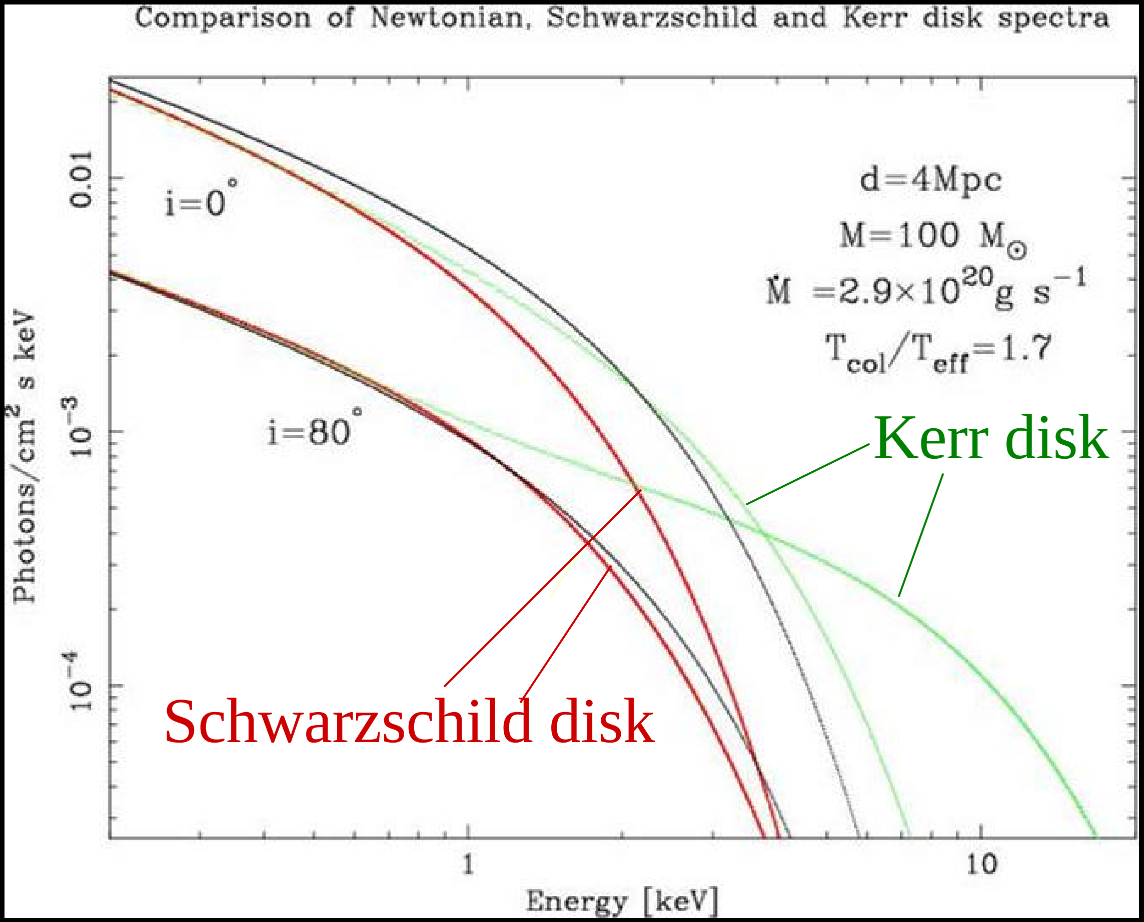
- Standard accretion disk around Kerr black hole may explain the hard disk spectra (Zhang, Cui and Chen 1997; Makishima et al. 2000)
  - R_{in} = 3 R_s (Schwarzschild) → 0.5 R_s (extreme Kerr)
  - higher disk temperature possible

Inclined Kerr disk is brighter in high energies



Laor, Netzer and Piran (1990)

“Transfer function” for a=0.998 available with xspec



- When the disk is face-on, the Kerr disk spectrum is not very different from the Schwarzschild case
- Hard emission from innermost parts is enhanced for inclined Kerr disks (Doppler boosts)
- Near-edge on Kerr disk has very harder spectrum

Application of Kerr disk spectra

- GRO J1655-40
  - $i=70^\circ$, d=3.2 kpc, $T_{col}/T_{eff}=1.7$ fixed
  - $M=16\ M_\odot$ with a=0.998 (extremely Kerr)
  - $M=7\ M_\odot$ suggests a=0.68 to 0.88 (Gielinski et al. 2001)
  - *Inclined Kerr disk model works to solve too-small mass problem*
  - 450 Hz QPO (Strohmayer 2001) supports a standard disk around a spinning black hole (Abramowicz and Kluzniak 2001)

Application of Kerr disk spectra

- IC342 Source 1
  - face-on Kerr disk (d=4Mpc, T_{col}/T_{eff}=1.7,a=0.998) M=29 $M_\odot$ and L=14 L_{Edd}
    - *Not much different from Schwarzschild case*
  - edge-on (i= 80°) Kerr disk (a=0.998) M= 355 $M_\odot$ and L=0.9 L_{Edd}
    - Super-Eddington problem may be solved *only if* the disk is highly inclined
    - Still unreasonably large mass required
  - Kerr disk model is not plausible for ULX, because disk inclination should be random

Slim disk (optically thick ADAF disk)

- Emerges when $L_{disk} \sim L_{Edd}$
- Optically thick and geometrically thick disk

$$F(r) \lesssim \frac{cGM}{\kappa r^2}\frac{h}{r},$$

where $F(r)$ is the energy flux, r the disk radius and h the half-thickness. Therefore,

$$L_{disk} = 2\int_{r_{in}}^{r_{out}} 2\pi r F(r) dr$$

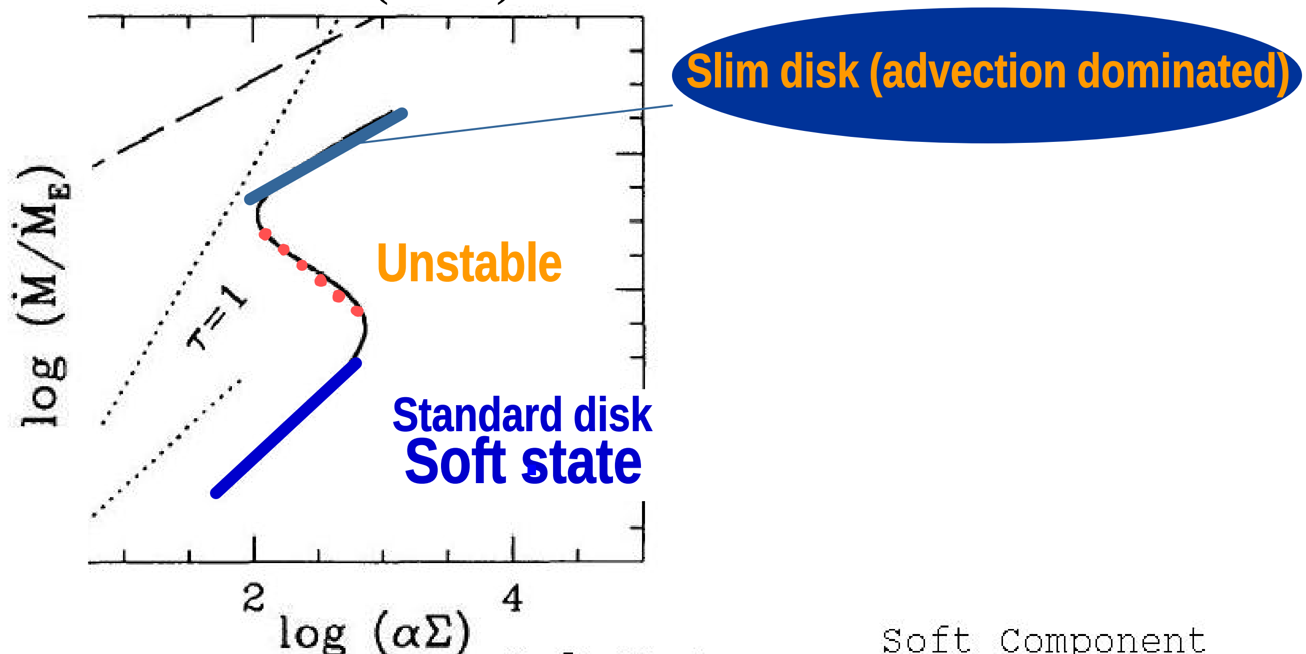
$$\lesssim \frac{4\pi cGM}{\kappa}\int_{r_{in}}^{r_{out}} \frac{h}{r^2} dr$$

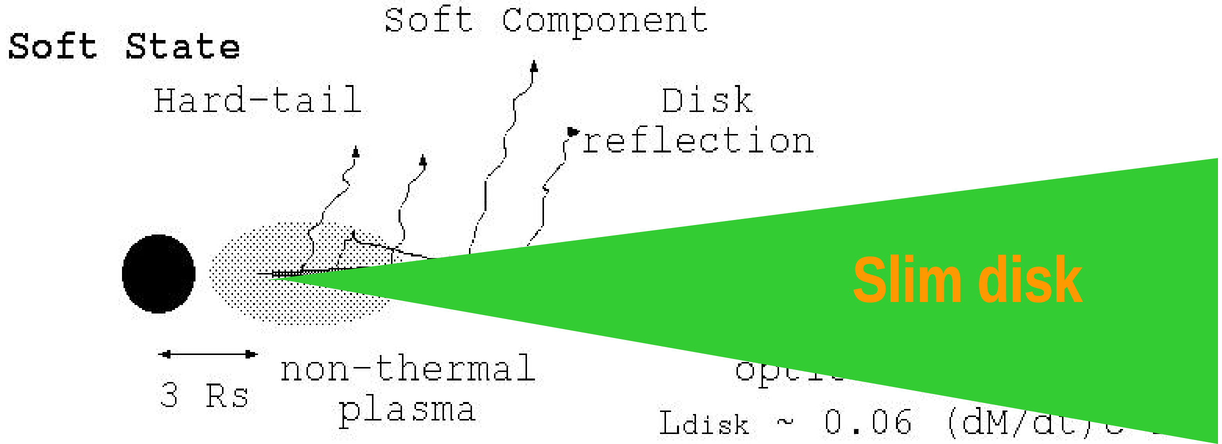
$$\approx L_{Edd}\left(\frac{h}{r}\right)\ln\left(\frac{r_{out}}{r_{in}}\right),$$

$h/r \sim 1$, $\ln(r_{out}/r_{in}) \sim 10$ for slim disk

→ L_{disk} can be $\sim 10\, L_{Edd}$

Abramowicz et al. (1995)





From recent study of Galactic black hole candidates

- Standard optically thick disk
  - Gravitational energy release → Radiation
  - $T(r) \propto r^{-0.75}$, R_{in} = const., $L_{disk} \propto T_{in}^{4}$

$\dot{M}$ increase | **T increase**

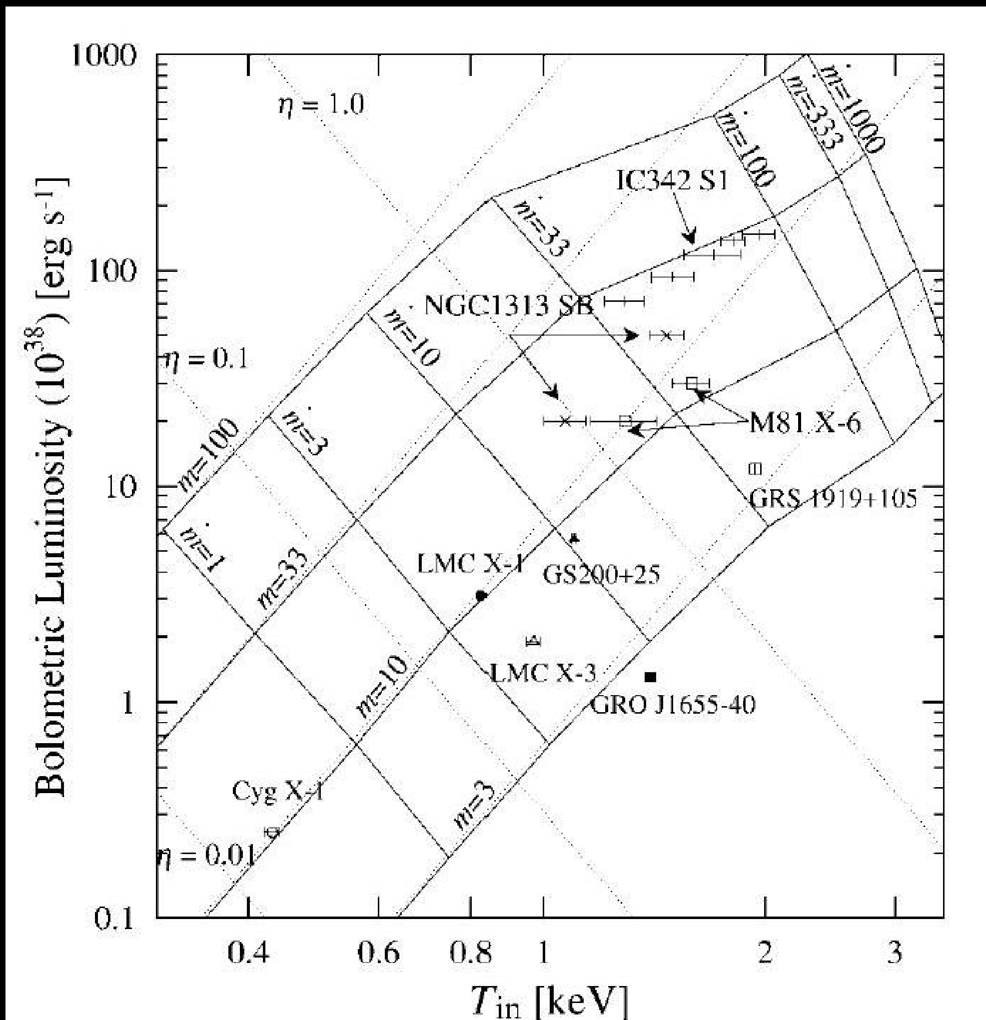
- Disk instability
  - Energy release → Comptonizing plasma
  - Disk compotonization

$\dot{M}$ increase | **T increase**

- Optically thick ADAF disk
  - Energy release → Advection
  - $T(r) \propto r^{-0.5}$, L_{disk} saturates

Disk Oscillation

Optically thick ADAF disk (slim disk)



Watarai et al. (2001)

L_{disk} saturates at high T_{in} (due to advection)

IC342 spectral change explained well

Strong disk comptonization

- IC342 source 1, Schwarzschild disk with $M=100\ M_{\odot}$, $L=L_{Edd}$ (Tin = 0.6 keV)
- Put comptonizing corona with $y=(4kT_e/mc^2)\tau_e \sim 0.5 \rightarrow$ soft photons comptonized and appear in higher energy band
- observed hard spectrum can be explained

Slim disk model for ULX

- Fitting ASCA IC342 Source 1 spectrum with Watrai's slim disk model (face-on, T_{col}/T_{eff} = 1.7, pseudo-Newtonian potential)
  - $M=23\ M_{\odot}$, $L_{disk} \sim 6\ L_{Edd}$
  - Slim disk model fit successful with reasonable mass and disk luminosity!

Summary

- Standard and near edge-on accretion disk around Kerr black hole can explain the hard spectra of Galactic superluminal jet sources
  - Apparently hard spectra are due to relativistic effects
- Super-Eddington luminosity and hard spectra of ULXs may be explained by Slim disk around a few tens of $M_{\odot}$ black hole
  - Such heavy black holes likely in massive star forming region