Origin of optically thick and low temperature coronae in super-Eddington accretion flows

(arXiv:2012.05386)

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Disk-Corona model

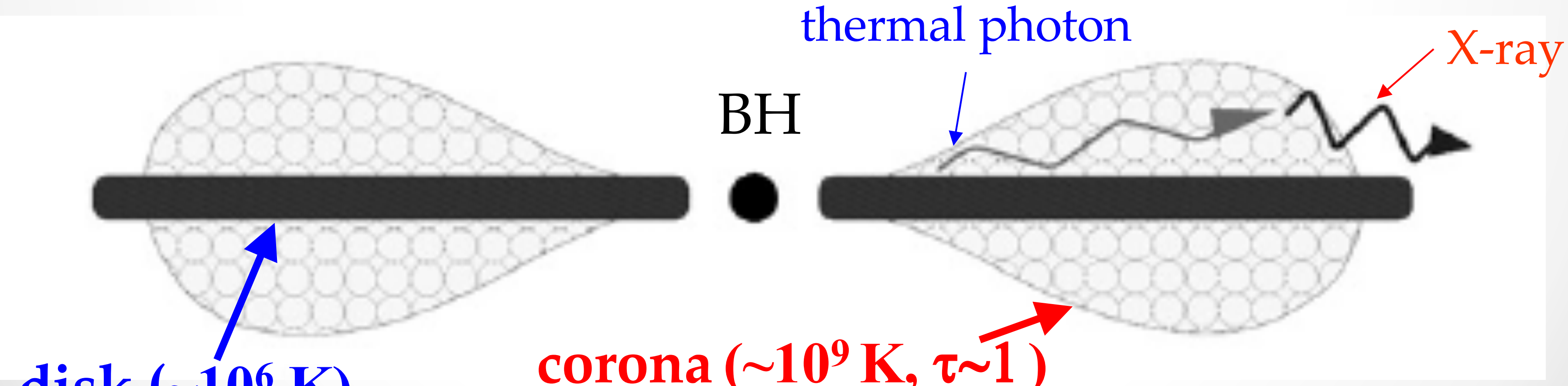
Liang & Nolan 1984; Haardt & Maraschi 1991

BH accretion flow = optically-thick, cool disk
+ tenuous, hot plasma (corona)

soft thermal photons … emitted from a disk

hard power-law X-ray … inverse Compton scattering in a corona

→ **account for the spectra of typical X-ray binaries and AGNs**



thermal photon

X-ray

BH

disk (~10^6 K)

corona (~10^9 K, τ~1)

(1) How to heat the corona
(2) How to load the plasma

uncertain

X-ray Spectra of Super-Eddington Accretors

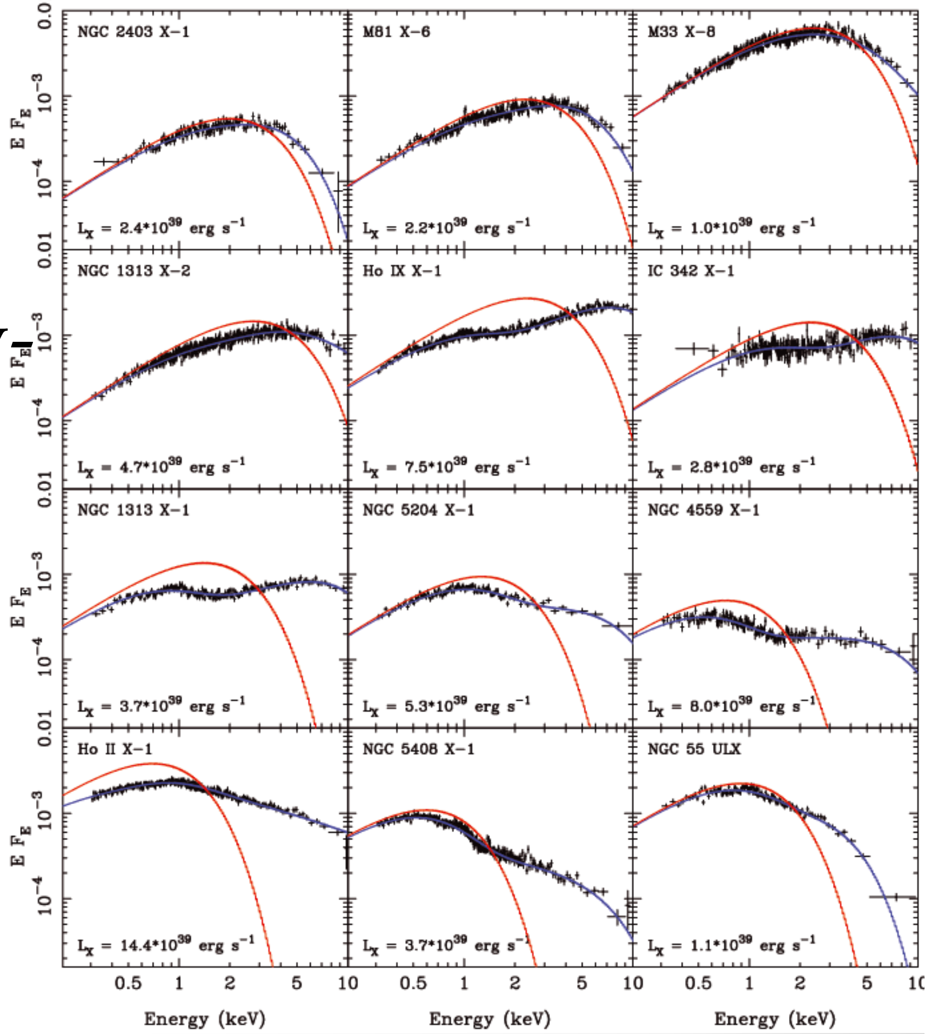
Ultraluminous X-ray sources:

(1) fitted by thermal (disk)+ hard (corona) component

(2) Comptonizing corona is relatively cool and optically thick **($T_c \sim$ 10 keV, $\tau_c \sim$ 5-10)** compared to that of sub-Eddington accretors ($T_c \sim$ 100 keV, $\tau_c \sim$ 1)

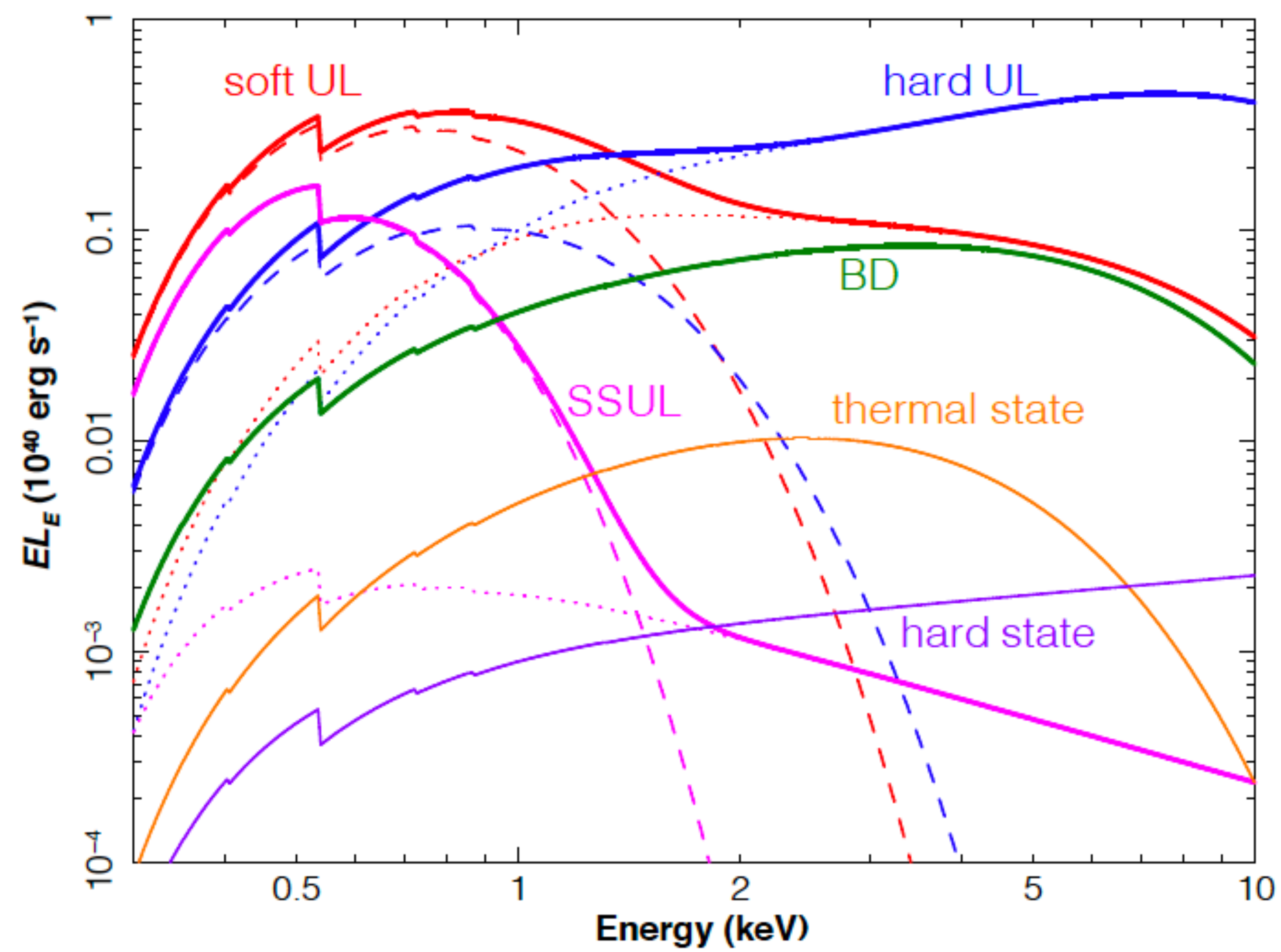
Similar in GRS 1915+105 (Vierdayanti et al. 2010) and NLS1 galaxies (Idogaki et al. 2018 etc.)

X-ray spectra of ULXs (Gladstone+ 09



Common to super-Eddington accretors?

Spectral states of ULXs



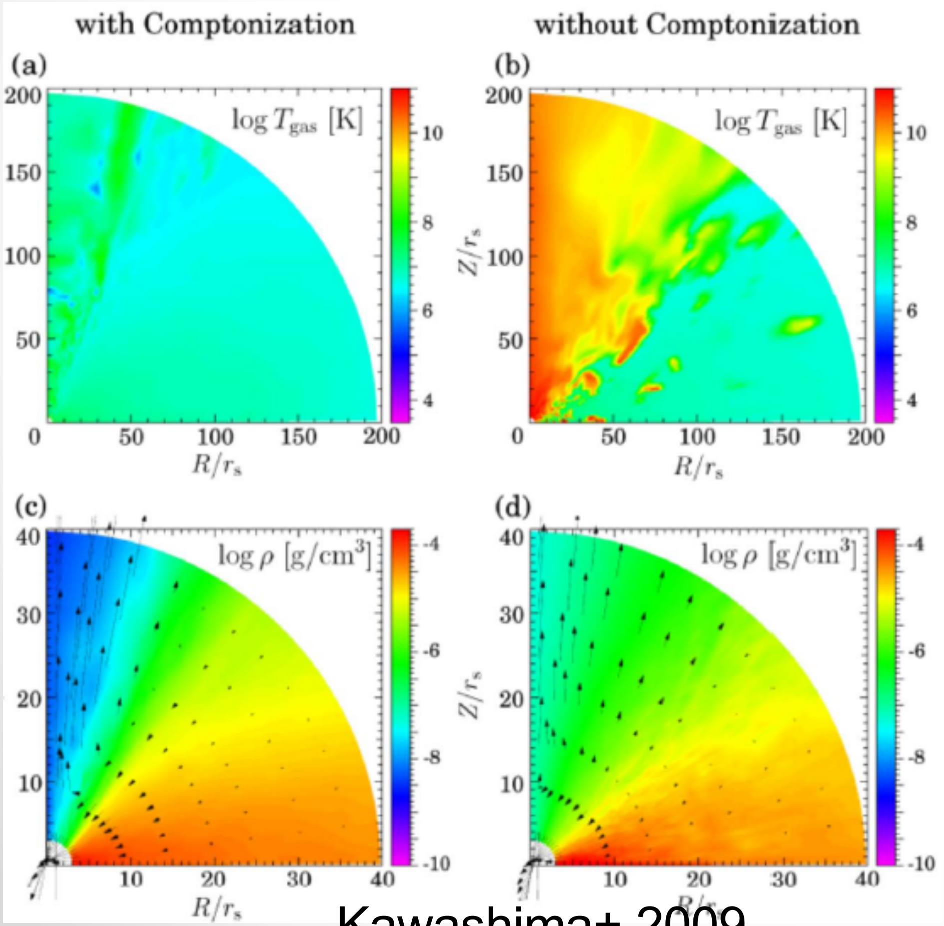
Kaaret+ 2017

What is the origin of corona for $L > L_{\rm Edd}$?

radiation-hydrodynamic simulations:

existence of upgoing hot plasma from the disk

(radiation pressure-driven outflow)



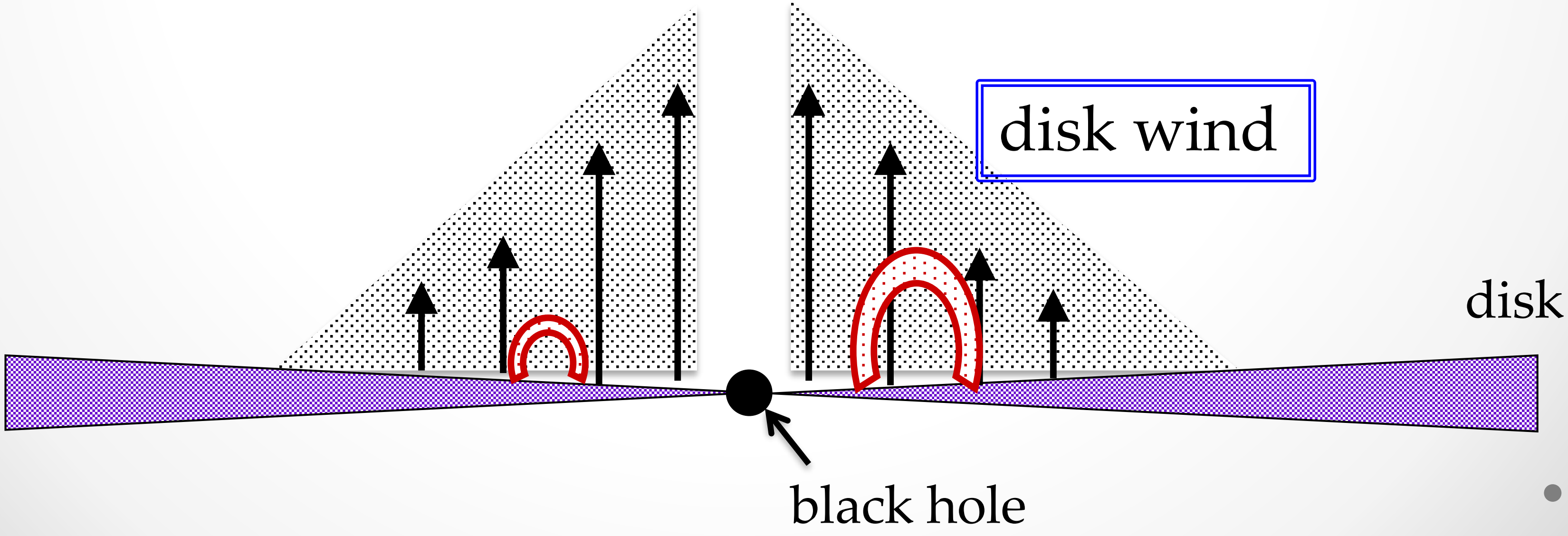
Kawashima+ 2009

Corona in super-Eddington accretion = radiation pressure-driven outflow?

Simple modelling

(NK & Mineshige arXiv:2012.05386)

- Inner disk region: radiation force > gravity
  → radiation pressure-driven disk wind
- Assumption: coronal plasma is supplied by the disk wind ("outflowing corona")
- Heating process: reconnection of magnetic loops emerged from the disk (Liu, Mineshige & Shibata 2002)



outflowing corona: density n_c

Standard disk: mass accretion rate is constant
Super Eddington disk: significant wind mass loss

➡ $$\dot{M}(r) \simeq \dot{M}_0 \left(r / r_{\mathrm{crit}} \right)^s \quad (0 < s < 1)$$

$$r_{\mathrm{crit}} = \left(\dot{M}_0 c^2 / L_{\mathrm{Edd}} \right) r_g$$: radiation force = gravity

Typical wind velocity: $v_{\mathrm{esc}} \sim (2GM_{\mathrm{BH}}/r)^{1/2}$

➡ $$n_c(r) = \frac{1}{4\pi r m_p v_{\mathrm{esc}}} \frac{d\dot{M}(r)}{dr}$$

outflowing corona: temperature T_c, size l_c

– **reconnection heating** = **inverse Compton cooling**

$$\frac{B^2}{4\pi}V_A \approx \frac{4k_{\rm B}T_c}{m_e c^2}\,cU_{\rm rad}\cdot\max\left(\tau_c,\tau_c^2\right)$$

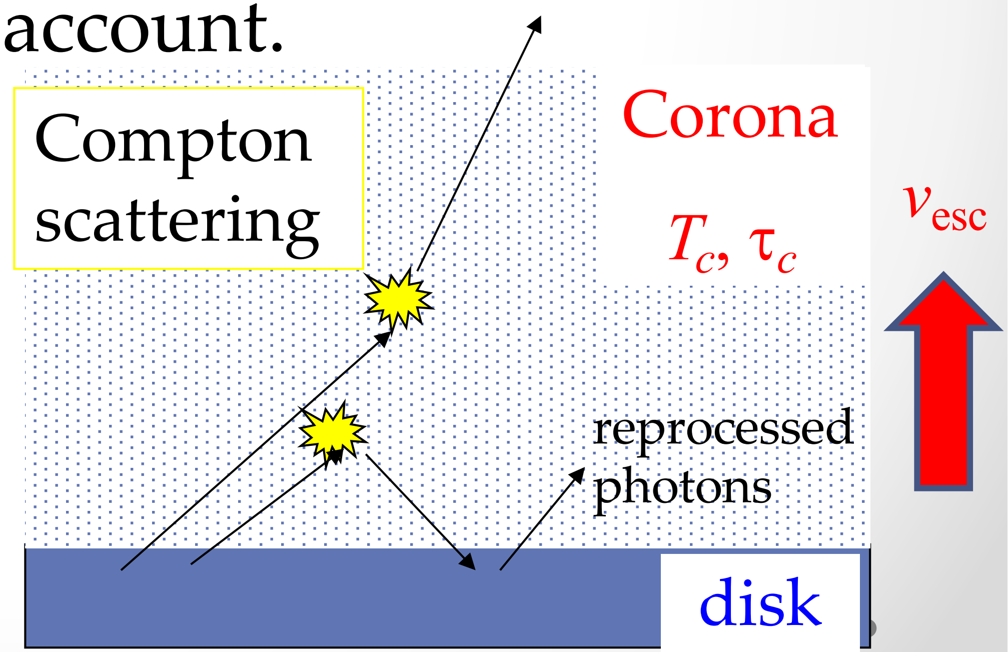
$\boldsymbol{B}$: magnetic field
... equipartition with disk pressure; $B^2/4\pi \sim \eta_B\, aT_{\rm disk}{}^4$)
$\boldsymbol{V_A} = B/(4\pi m_p n_c)^{1/2}$: Alfvén velocity
$\boldsymbol{U}_{\bf rad}$: seed photon energy density
... Limited by the Eddington flux: $\sim L_{\rm Edd}/(4\pi r^2 c)$
$\boldsymbol{\tau}_{\bf c} = n_{\rm c}\sigma_{\rm T} l_{\rm c}$: Thomson scattering optical depth

\- scale height of the corona: $l_{\rm c}(r) \sim r$
wind's escape time = photon's diffusion time
→ $l_c \sim \min\,[c/(v_{\rm esc} n_e \sigma_T),\, r]$

Spectrum Calculation

- seed photon: Planck distribution $T_{\rm seed} = (U_{\rm rad}/a)^{1/4}$
- Monte Calro simulation (Podznyakov et al. 1977) at each radius, using $T_c(r)$ and $\tau_c(r)$
- Only Compton scattering is considered
- Reprocessed photons are also taken into account.
- Inverse Compton cooling of the corona is consistently taken into account.

Count all photons emerging from the upper boundary of the corona

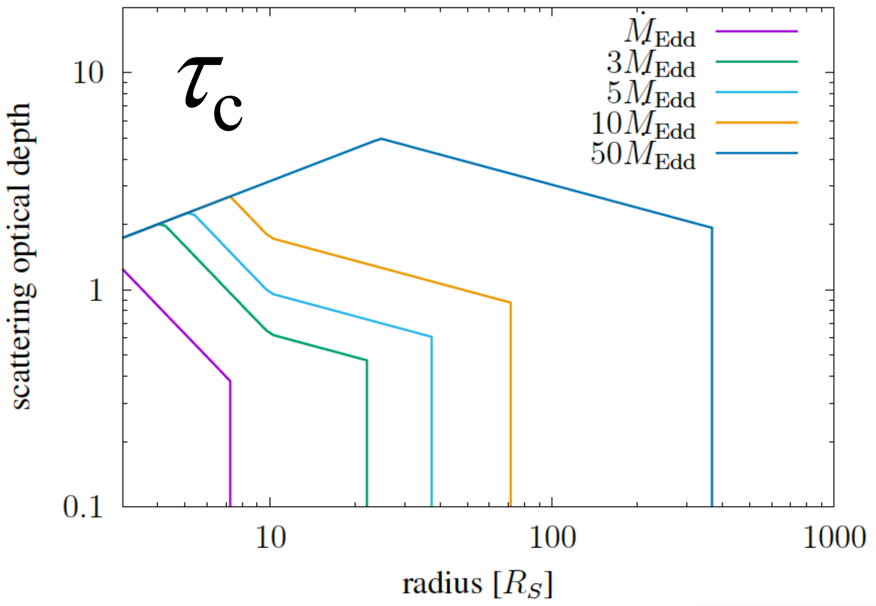


Results : optical depth & temperature

$M_{\rm BH} = 10\ M_{\rm sun}$

$s = 0.15$ ← from RHD simulations (Kitaki+ 18, 20)

$\eta_R = 0.015$ ← maximal heating

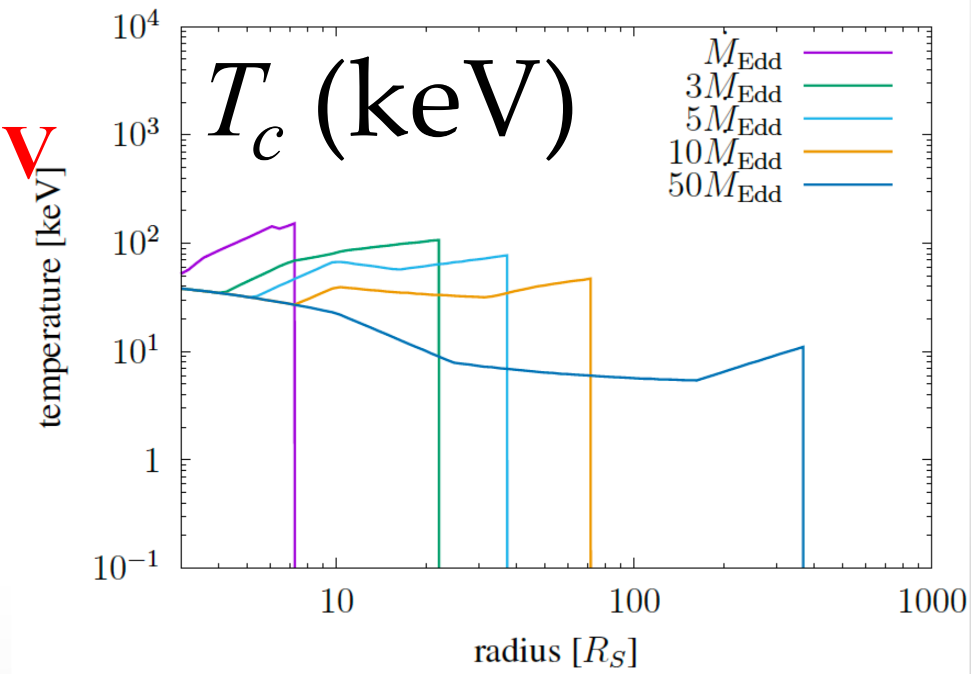


Scattering optical depth

… typically **$\tau_c \sim$ 1-7**

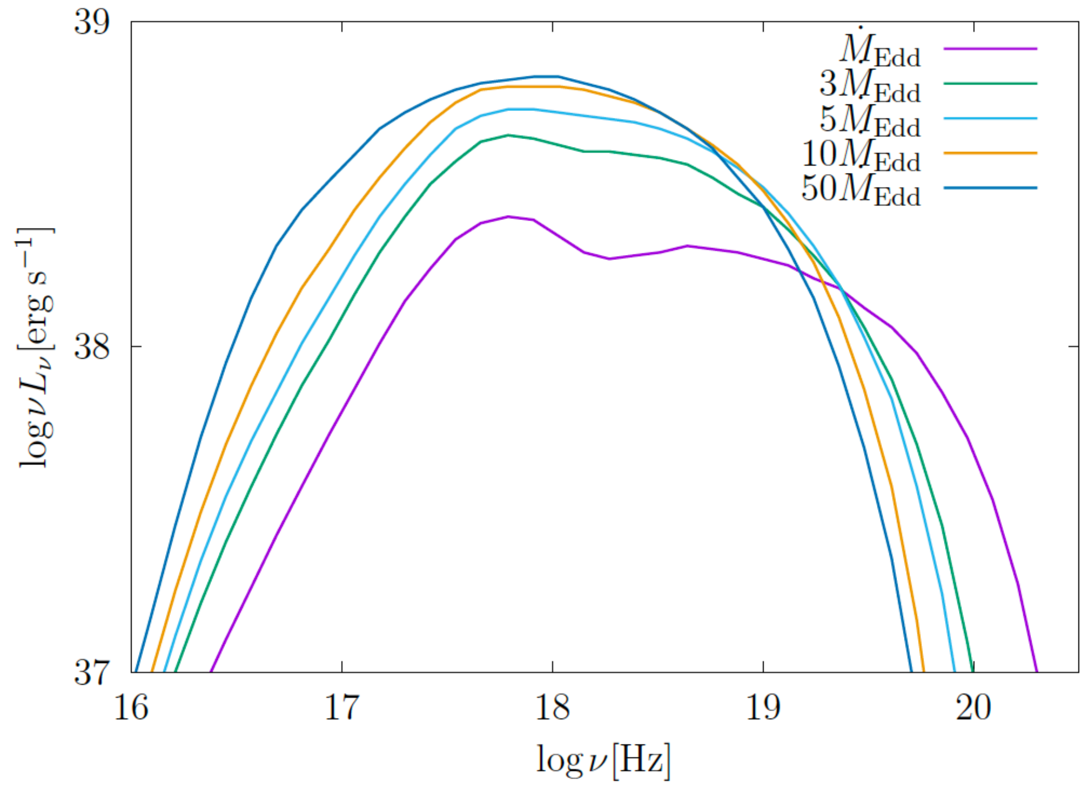
temperature

… typically **$T_c \sim$ a few × 10 keV**



Observationally inferred coronal properties are fairly reproduced.

Results : Spectra



Soft thermal bump + hard Comptonized component

Spectral peak energy
~ a few keV

~ Soft UL / Broadened Disk / thermal states of ULXs

$\dot{M}$ increases

→ The peak frequency of the Comptonized component decreases.
The cutoff frequency of the Comptonized component decreases (∵ efficient Compton cooling).

Why do we have optically thick & cool corona?

sub-Eddington accretion flow

- Coronal plasma is fed by the evaporation driven by heat conduction

→ When corona becomes optically thick enough, due to Compton cooling, the temperature difference between corona and disk gets smaller

→ Evaporation driven by heat conduction is suppressed

→ Corona cannot get too optically thick.

super-Eddington accretion flow

- Coronal plasma is fed by radiation pressure-driven disk wind, which would not be suppressed even if corona becomes very optically thick

→ Corona would be cooled via efficient Compton scattering.

Summary (see arXiv:2012.5386 for details)

- We propose a simple model for optically-thick and cool corona, inferred from the observations of super Eddington accretor such as ULXs, NLS1, etc.
  - (1): corona = radiation-driven wind
  - (2): Energy balance between magnetic reconnection heating and inverse Compton cooling in the corona
- Using Monte Carlo simulations, we solve the transfer of photons in the outflowing corona taking into account Compton scattering

→ $T_c \sim$ **O(10) keV,** $\tau_c \gtrsim$ **1-10** are naturally reproduced

→ **SED**: soft thermal bump + Compton component typical ULXs' spectra are fairly reproduced