Photon Spectra of Super-Critical Black Hole Accretion Flows

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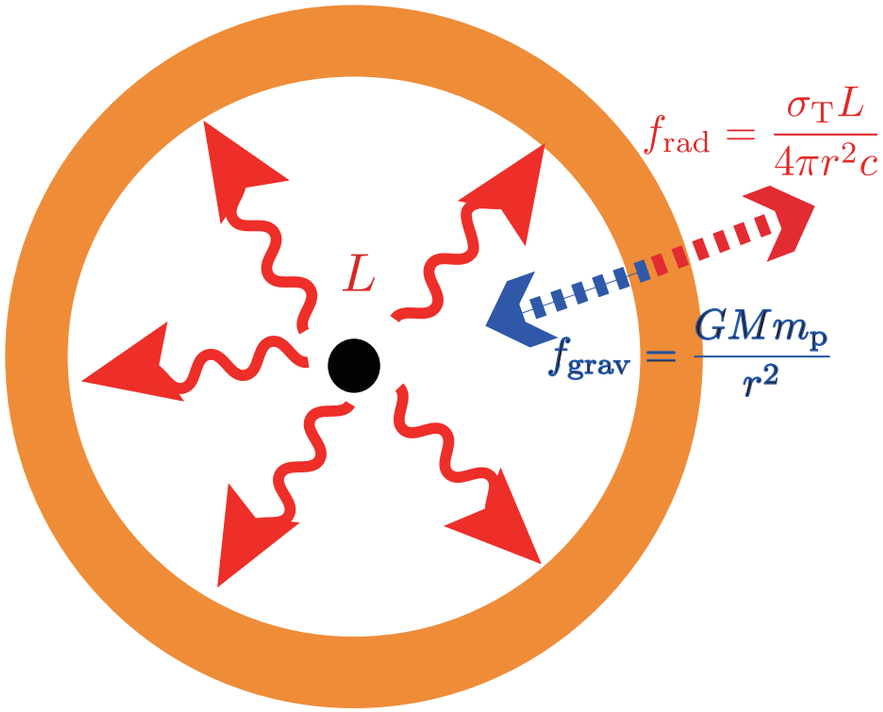
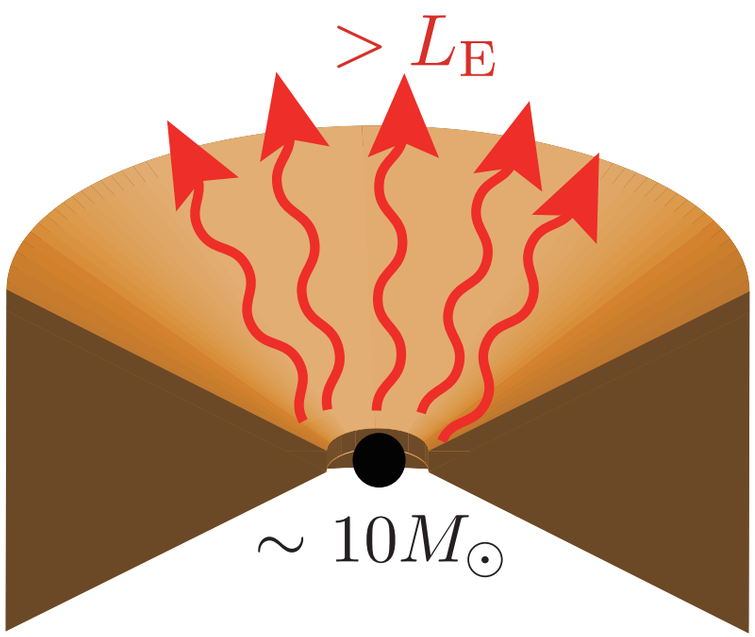
Supercritical Accretion Flows

- spherical accretion:
  sub-Eddington $L \leq L_{\rm E}$
  ($L_{\rm E}$: Eddington luminosity)
- disk accretion:
  anisotropic radiation
  → supercritical accretion
  is feasible
  → super-Eddington $L \gtrsim L_{\rm E}$
- candidates :

  powerful jet sources (SS433, S26)
  Narrow Line Seyfert I, OVV quasars,
  microquasar (GRS1915+105),
  ultraluminous X-ray sources



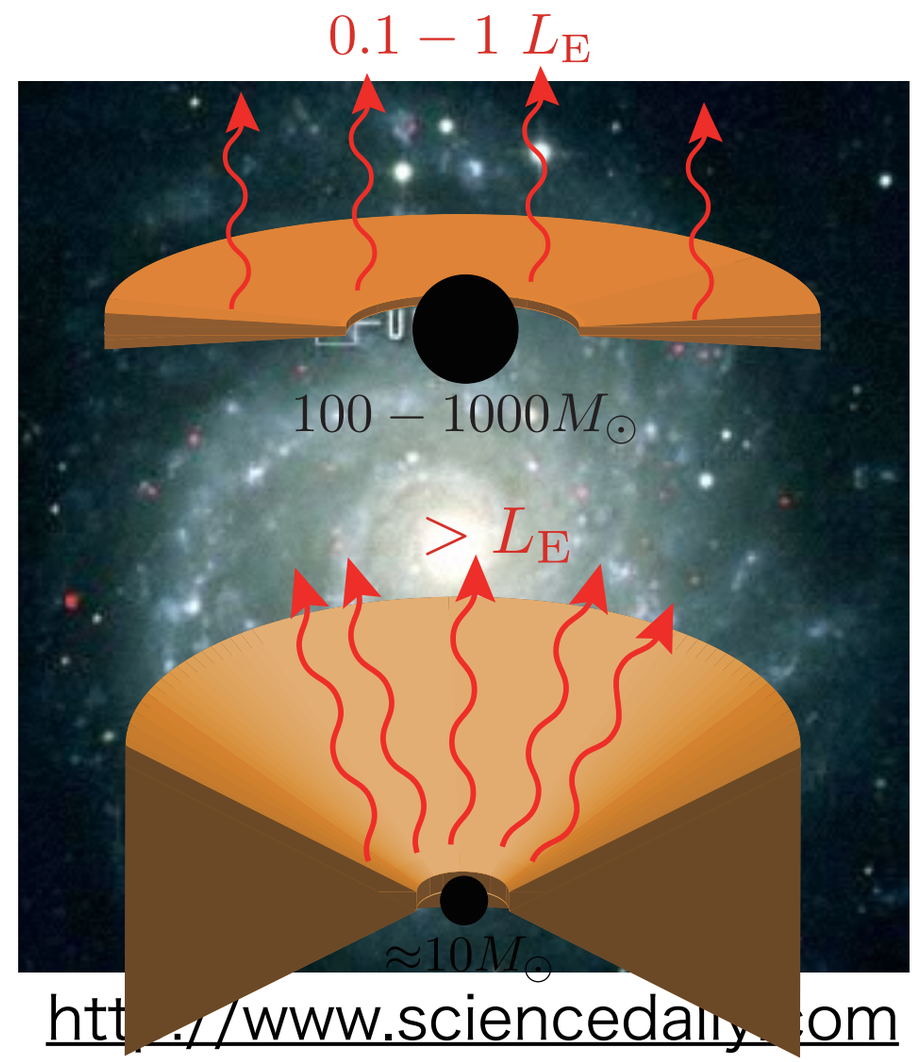


Ultraluminous X-Ray Sources (ULXs)

- ULXs are observed in off-center region of nearby galaxies.
- Luminosity: $L_{\rm X} = 10^{39-41}[{\rm erg \cdot s^{-1}}]$

  $> L_{\rm E}$ for stellar-mass BHs

(A)subcritically accreting intermediate mass BH?
or
(B)supercritically accreting stellar-mass BH?



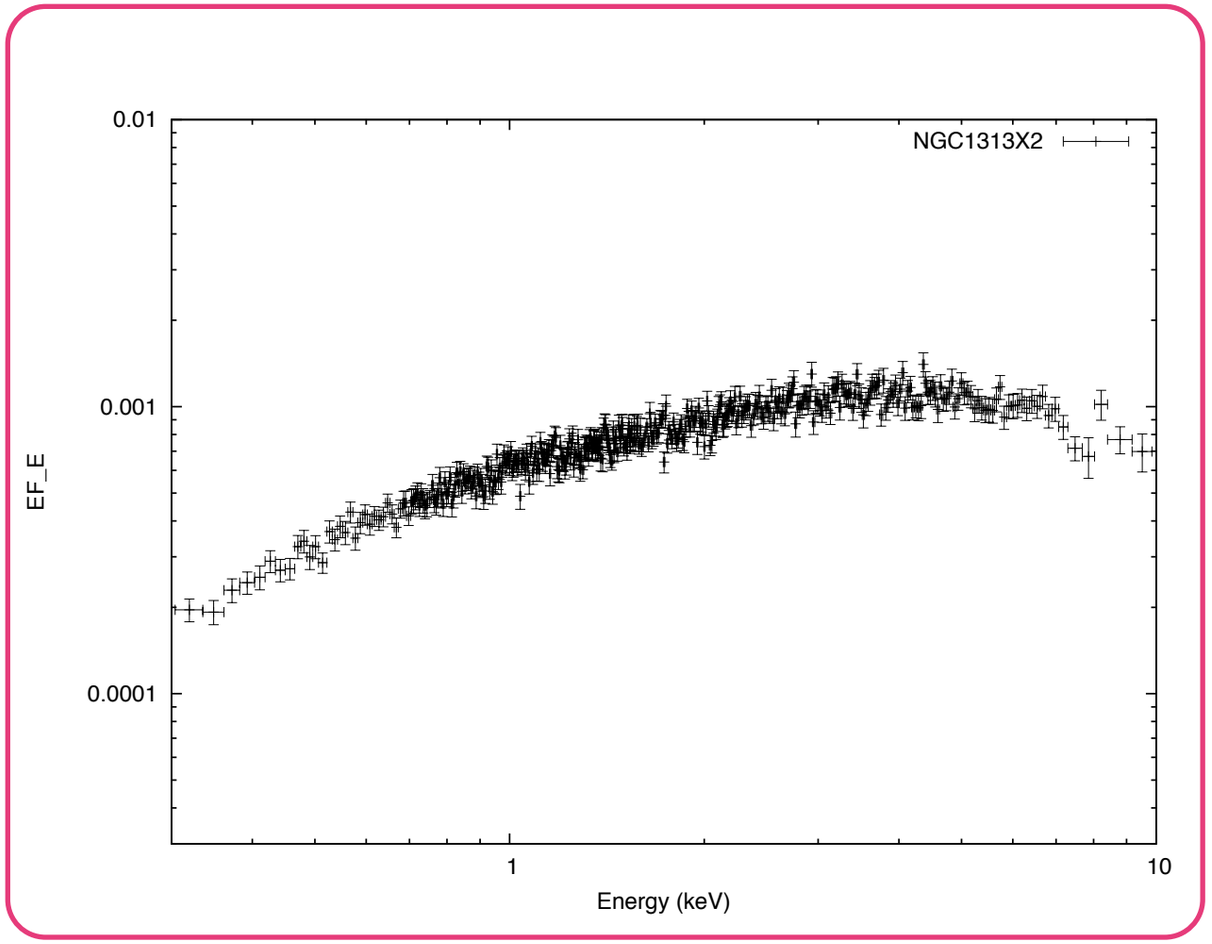
http://www.sciencedaily.com

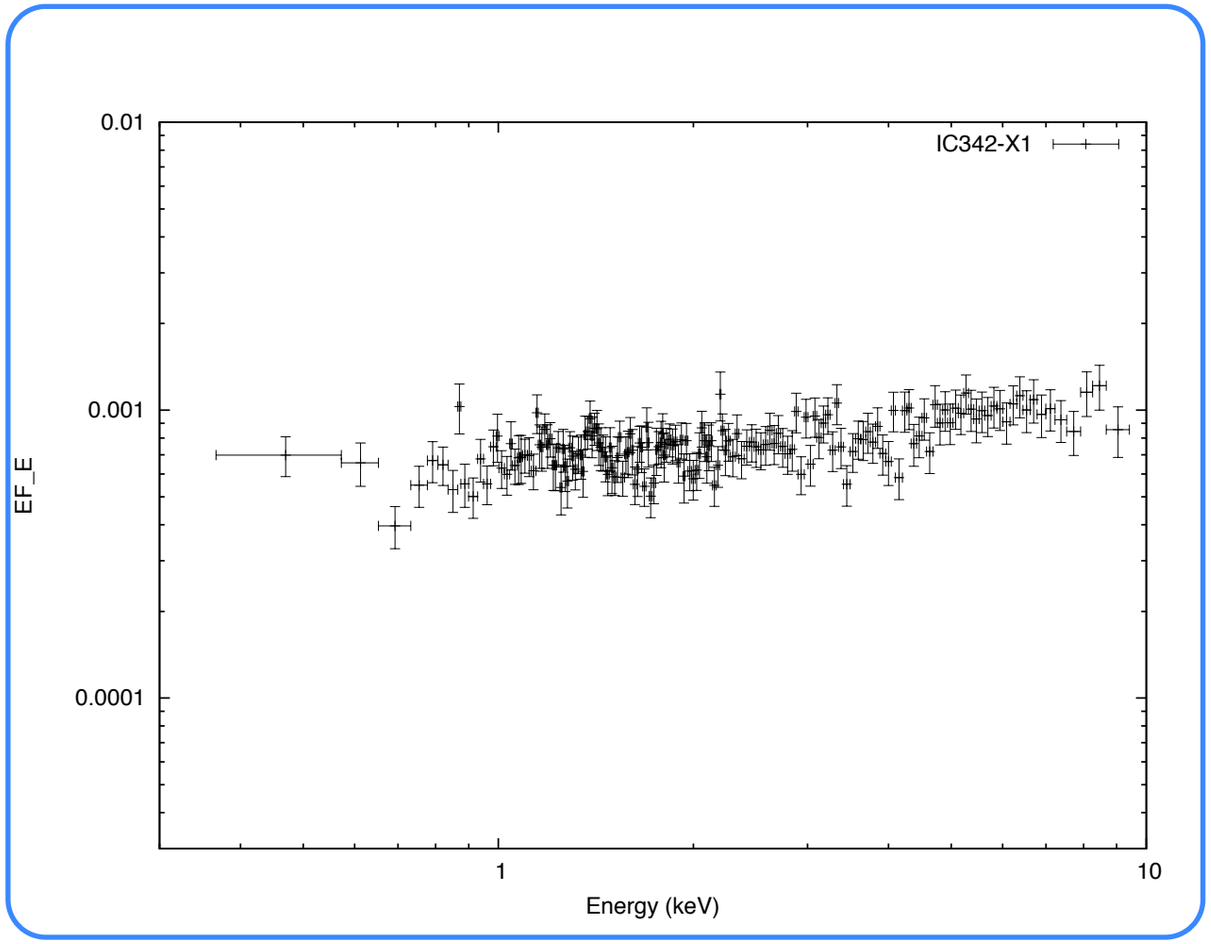
Recently, the discovery of a supercritically accreting NS (M82 X-2) has been reported (Bachetti et al. 2014)

ULXs show spectral features different with galactic BHCs nor AGNs.

Studies of SEDS are expected to be a key to understand ULXs.

SEDs of ULXs - New Spectral State!
(e.g. Gladstone et al. 2009)



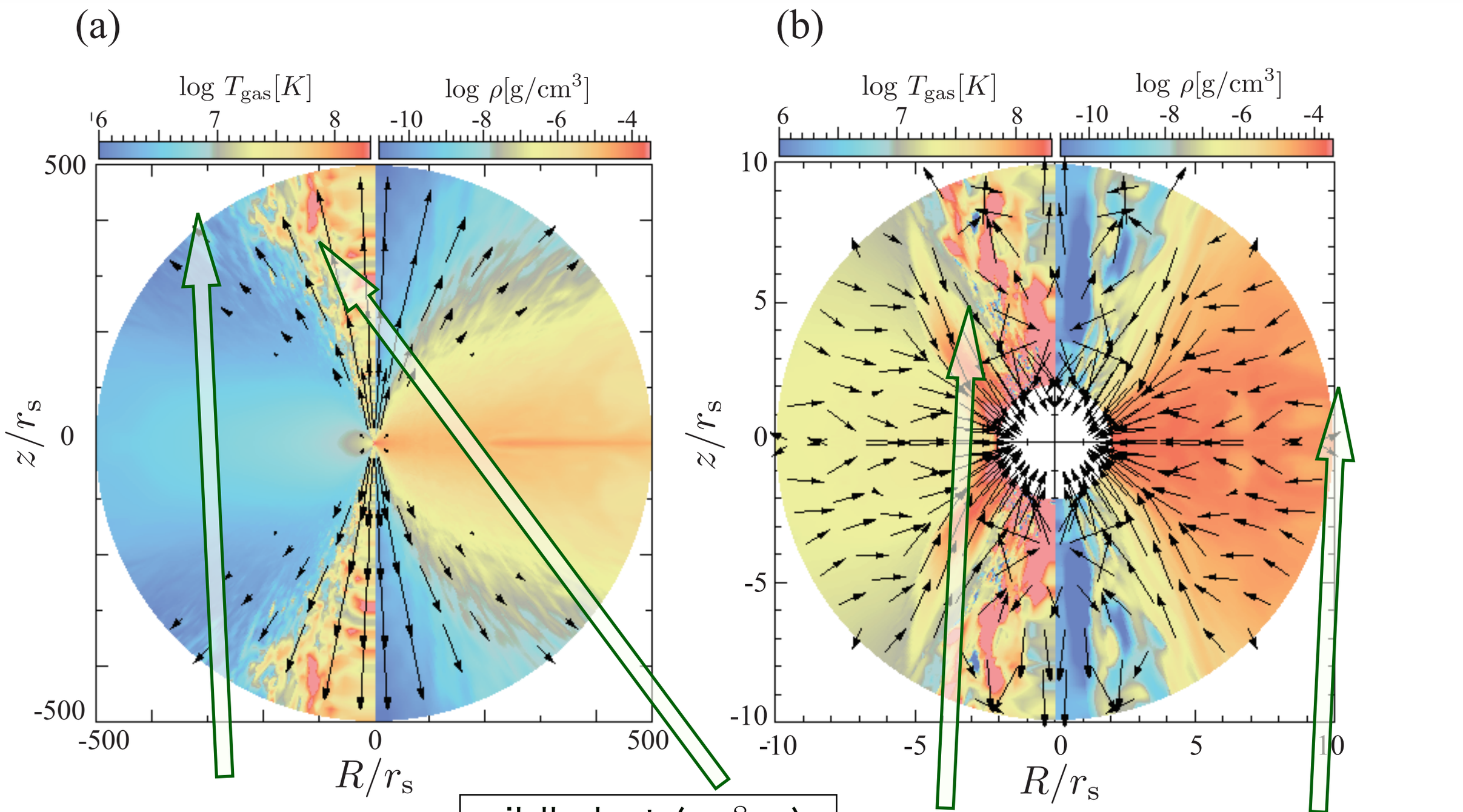


The data are kindly sent to us by Dr. Gladstone.

ULXs show the hard power-law component, which
(1) rolls over around 5 keV
or (2) extends up to 10 keV.

Rad-HD simulations are needed to study super-Eddington Flows.

Structure of Super-Critical Accretion Flow with Compton-Cooled Outflow (Axisymmetric 2D Rad-HD Simulation, $M_{\rm BH} = 10 M_\odot$)



cool($10^{6.5}$K), dense and slow($< 10^{-2}c$) outflow

mildly hot (10^8K), sub-relativistic funnel jet

shock-heated region(10^8K)

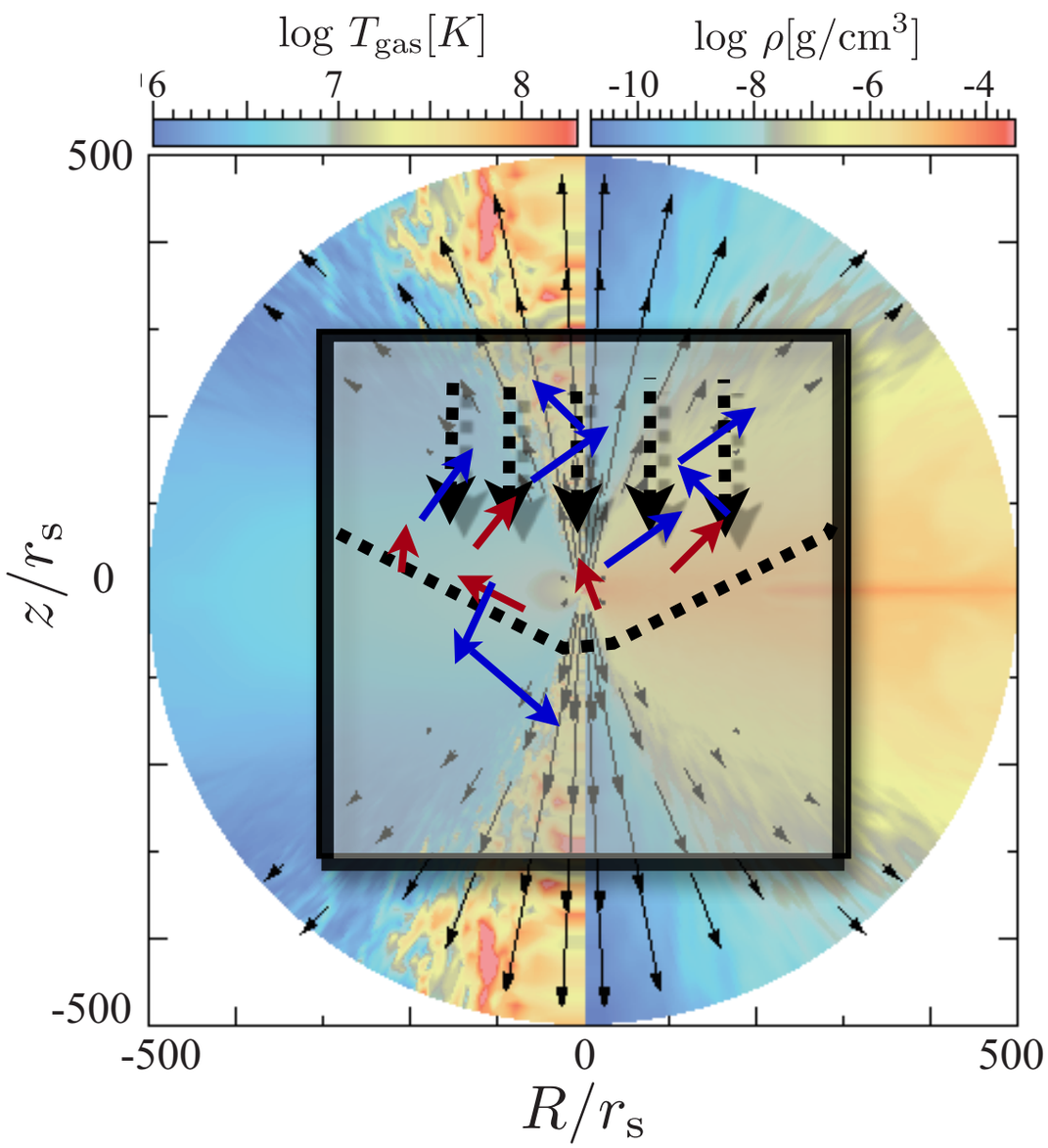
rad. pressure dominant disk

Calculation Model of SEDs

Rad-HD simulation

$\rho\ , T_{\rm gas},\ \ v$

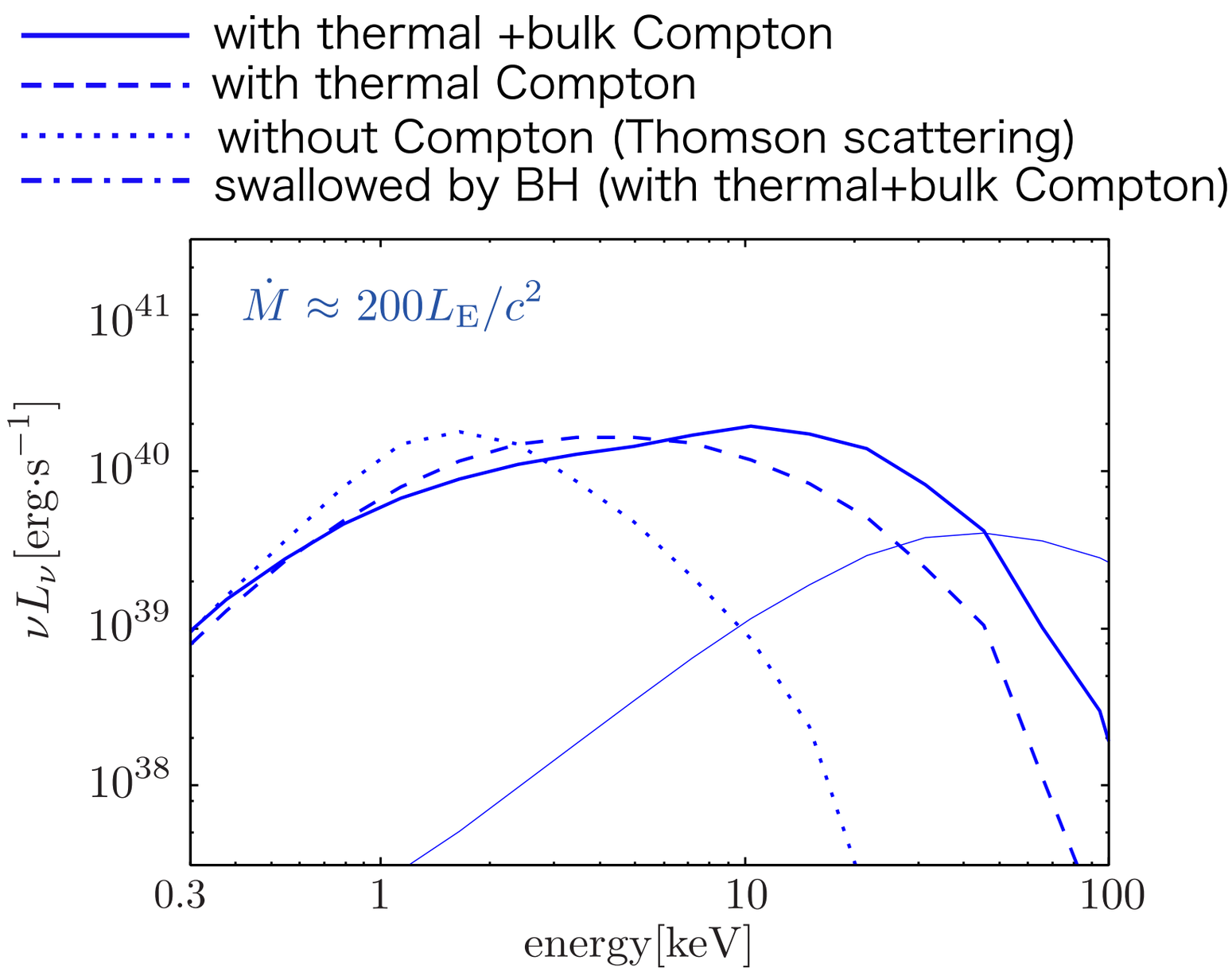
solve the photon transport using Monte-Carlo method



1. Identify surface where $\tau_{\rm eff} = 10$
2. generate seed photon from a point above the surface obtained by step (1)
   - consider bremss. emission
   - Taking into account special relativistic effects (Doppler shift & aberration due to bulk motion)
3. Solve photon transport by using Monte-Carlo method
   - free-free absorption
   - photon-trapping effect
   - thermal & bulk Comptonizaton

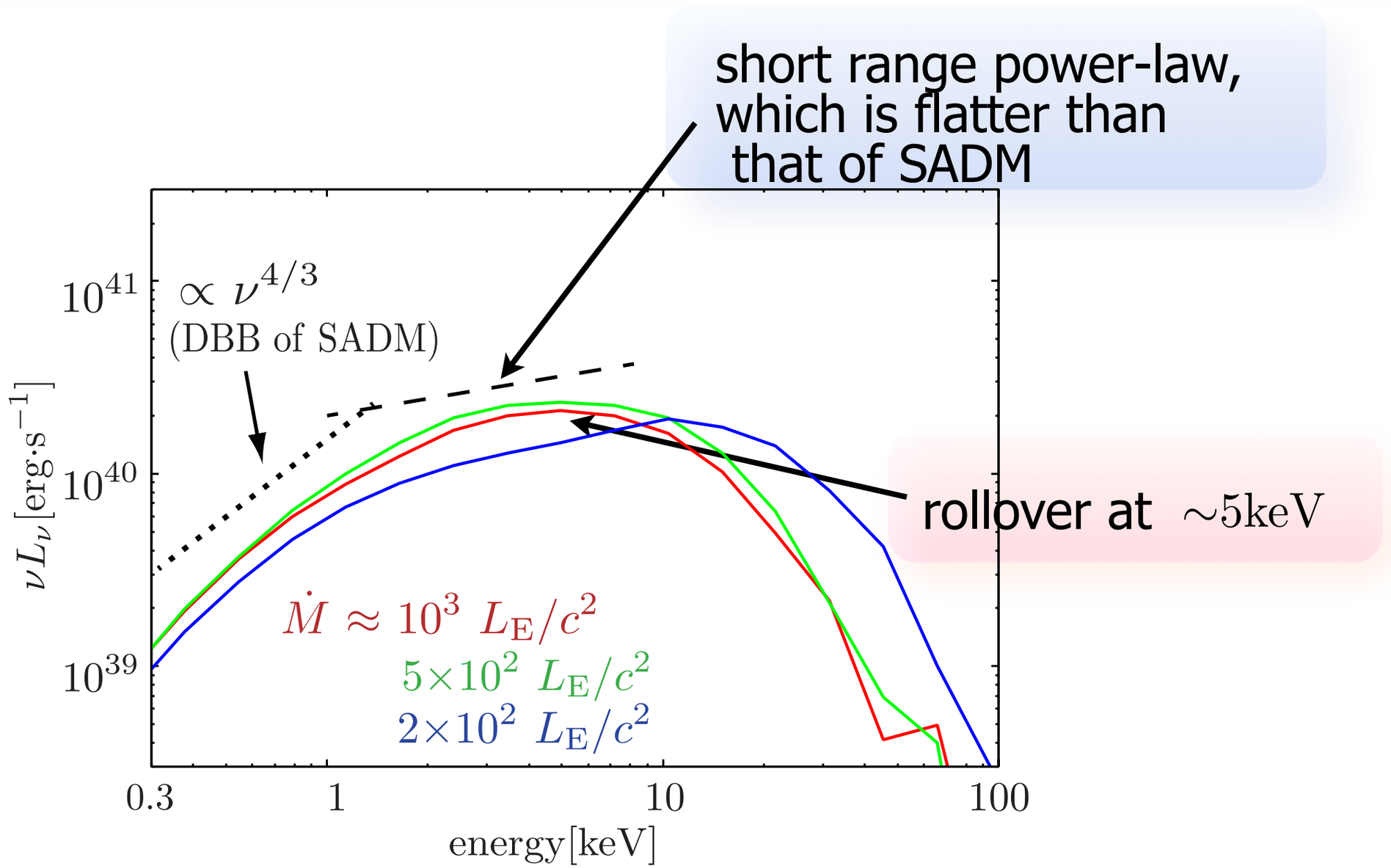
output SED

Effect of Compton Scattering on SED



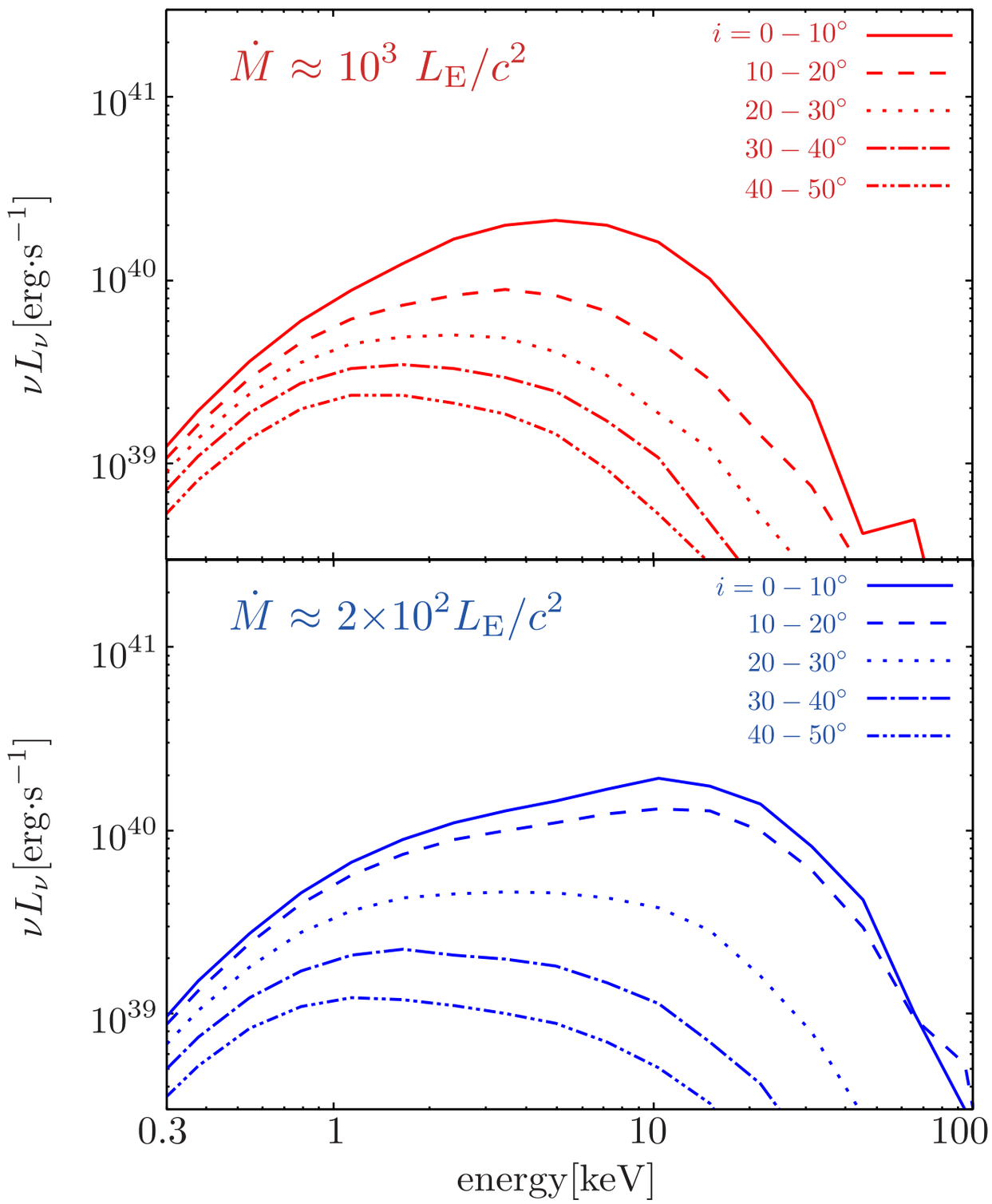
- Thermal and bulk Comptonization harden SEDs.
- In the hot plasma formed near the BH, the photons are upscattered by thermal inverse Compton scattering.

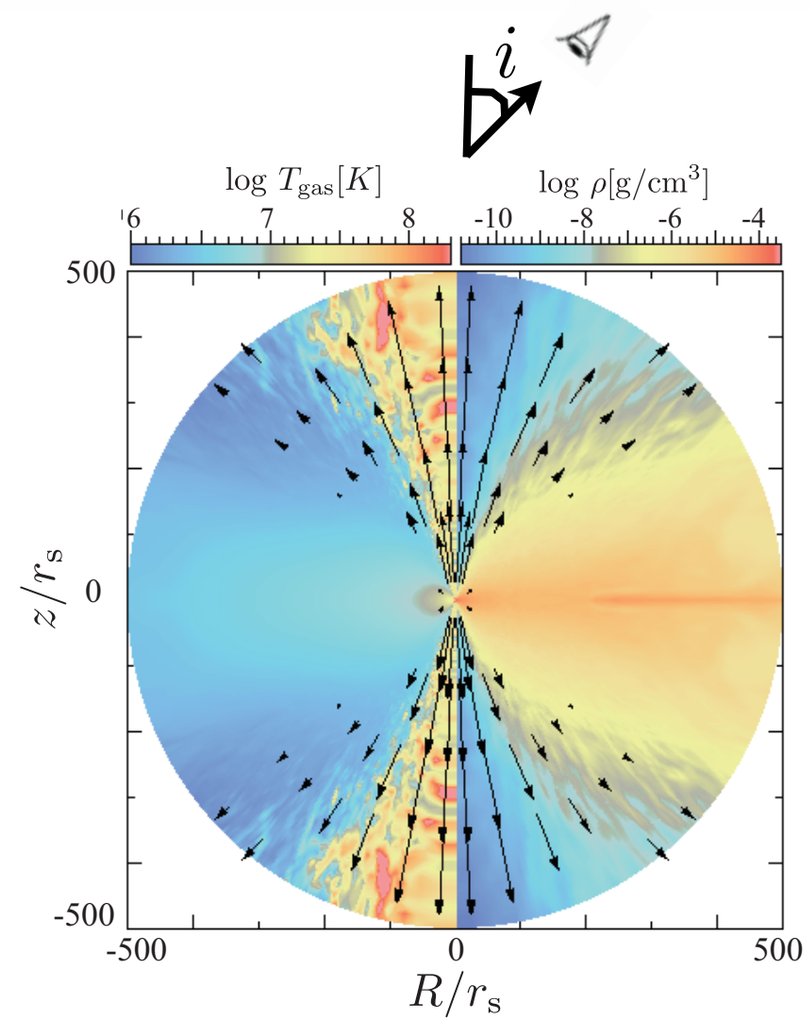
Dependence of $\dot{M}$ on SEDs



- When the mass accretion rate is lower, the power-law extending up to 20 keV appears.
- When the mass accretion rate is higher, rollover at 5 keV appears.

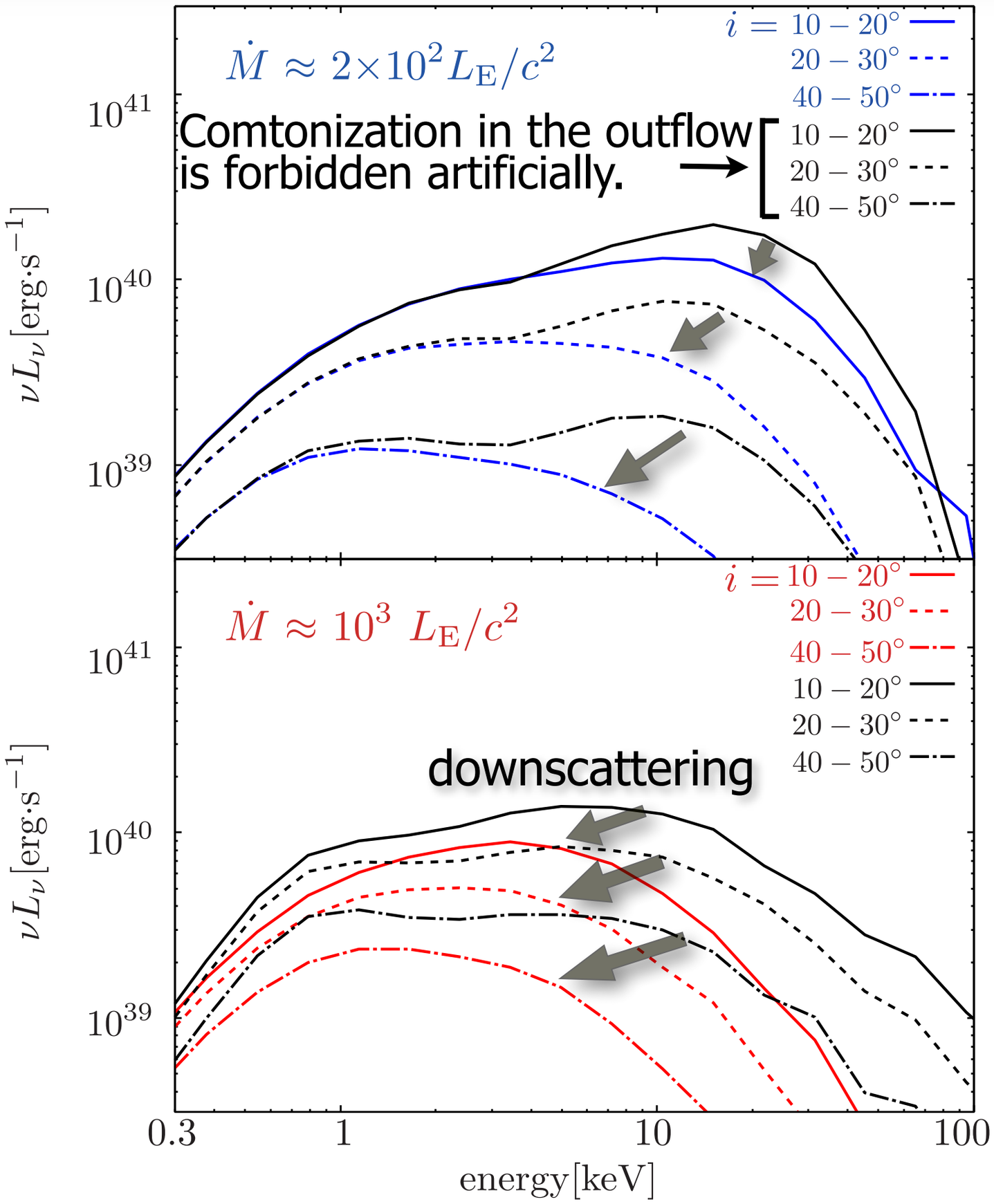
Dependence of SEDs on the viewing angle "i"

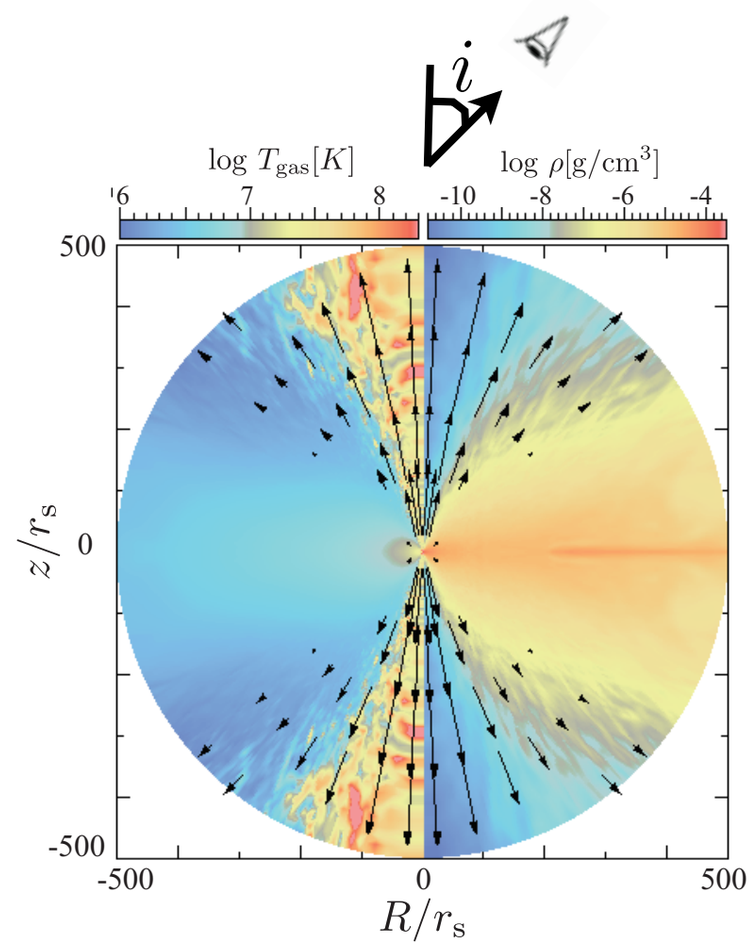




- When the viewing angle is smaller, SEDs become harder.
- For $\dot{M} \approx 2\times10^2 L_E/c^2$, the rollover around 5keV also appears when the viewing angle is large.

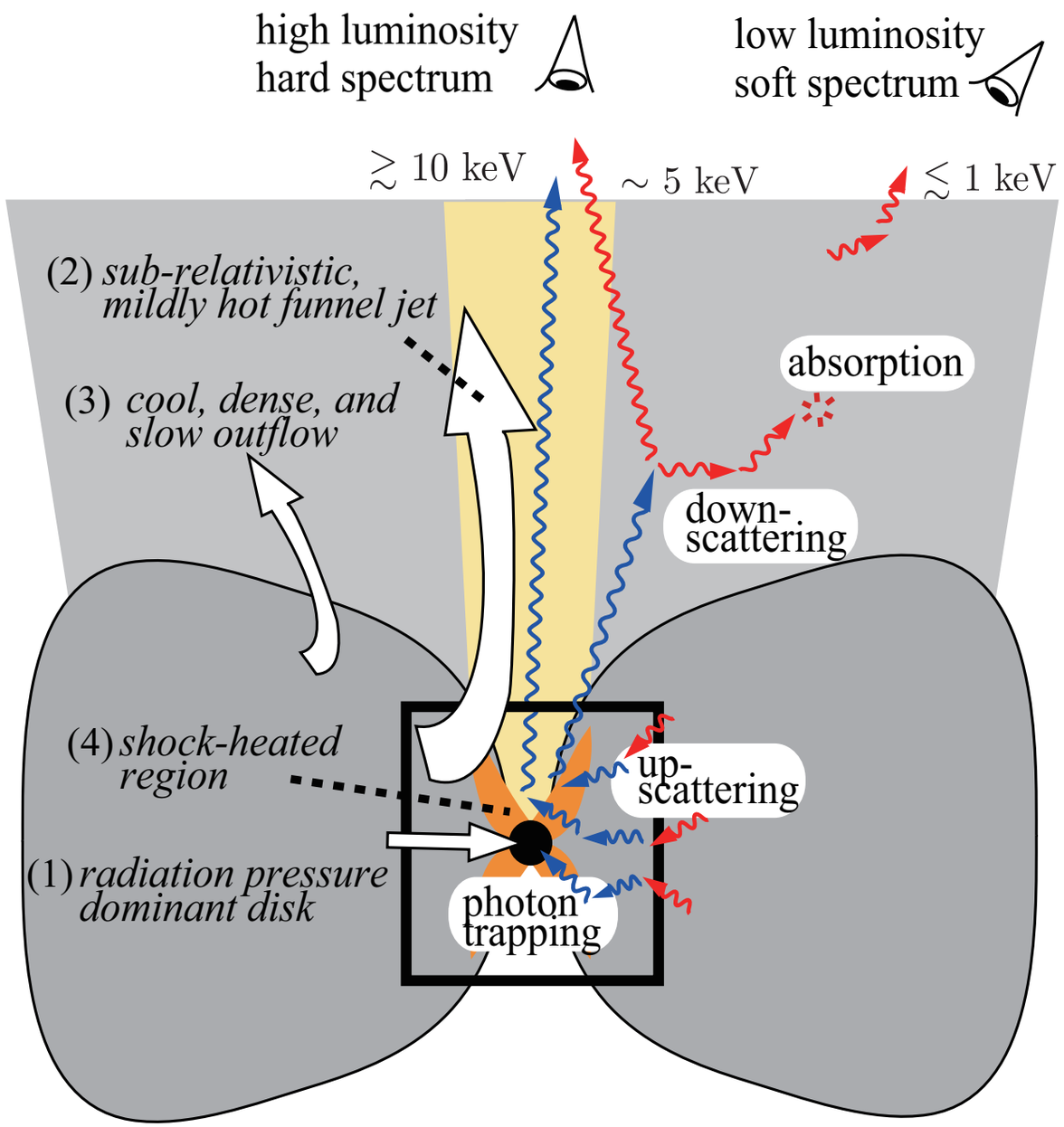
Spectral Softening in the Outflow

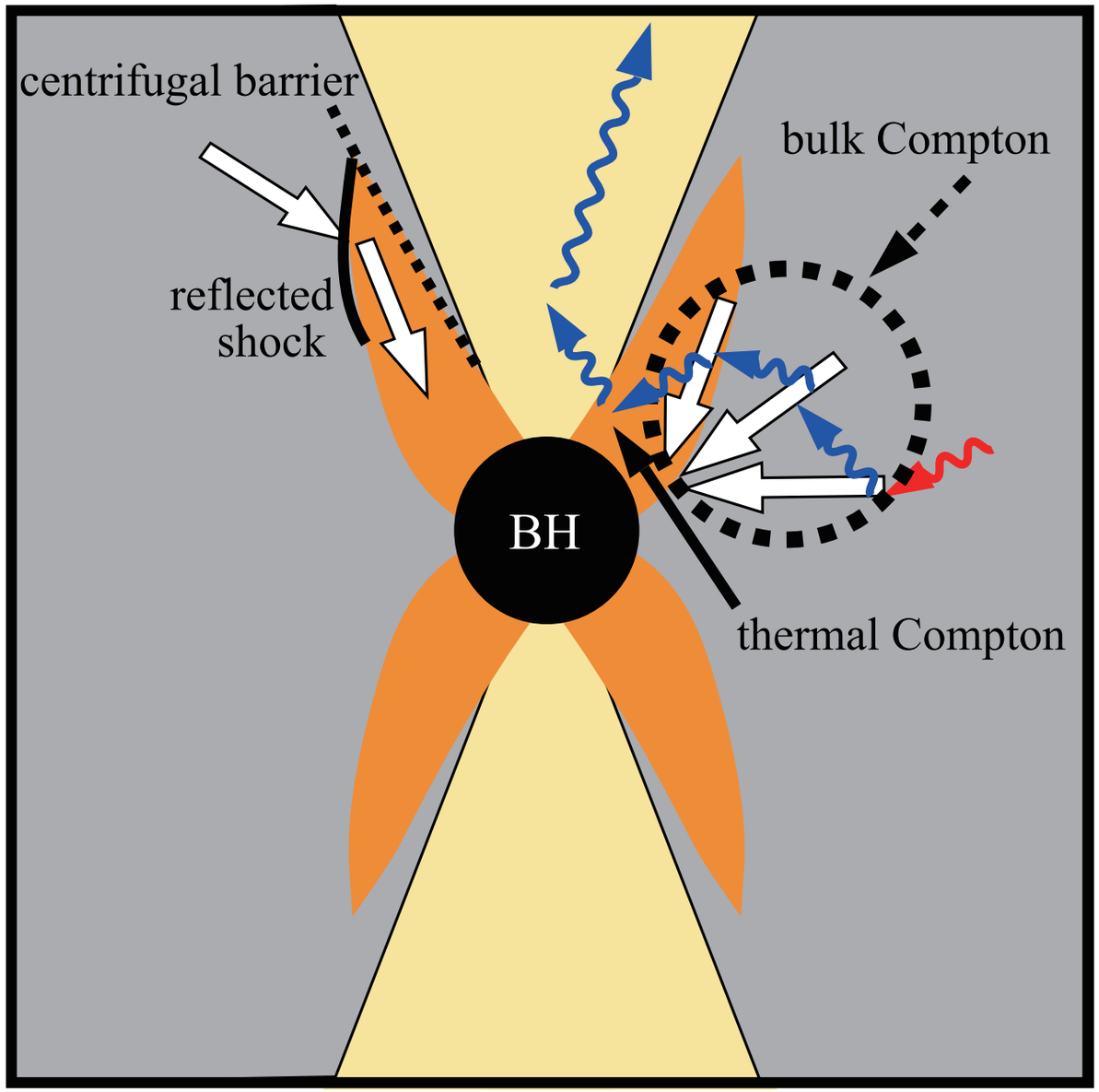




When $\dot{M}$ is higher or inclination angle is larger, SEDs become softer. This is because more of observable photons are Compton downscattered in the cool outflow.

Structure of Super-Eddington Accretion Flow & Trajectories of Photons





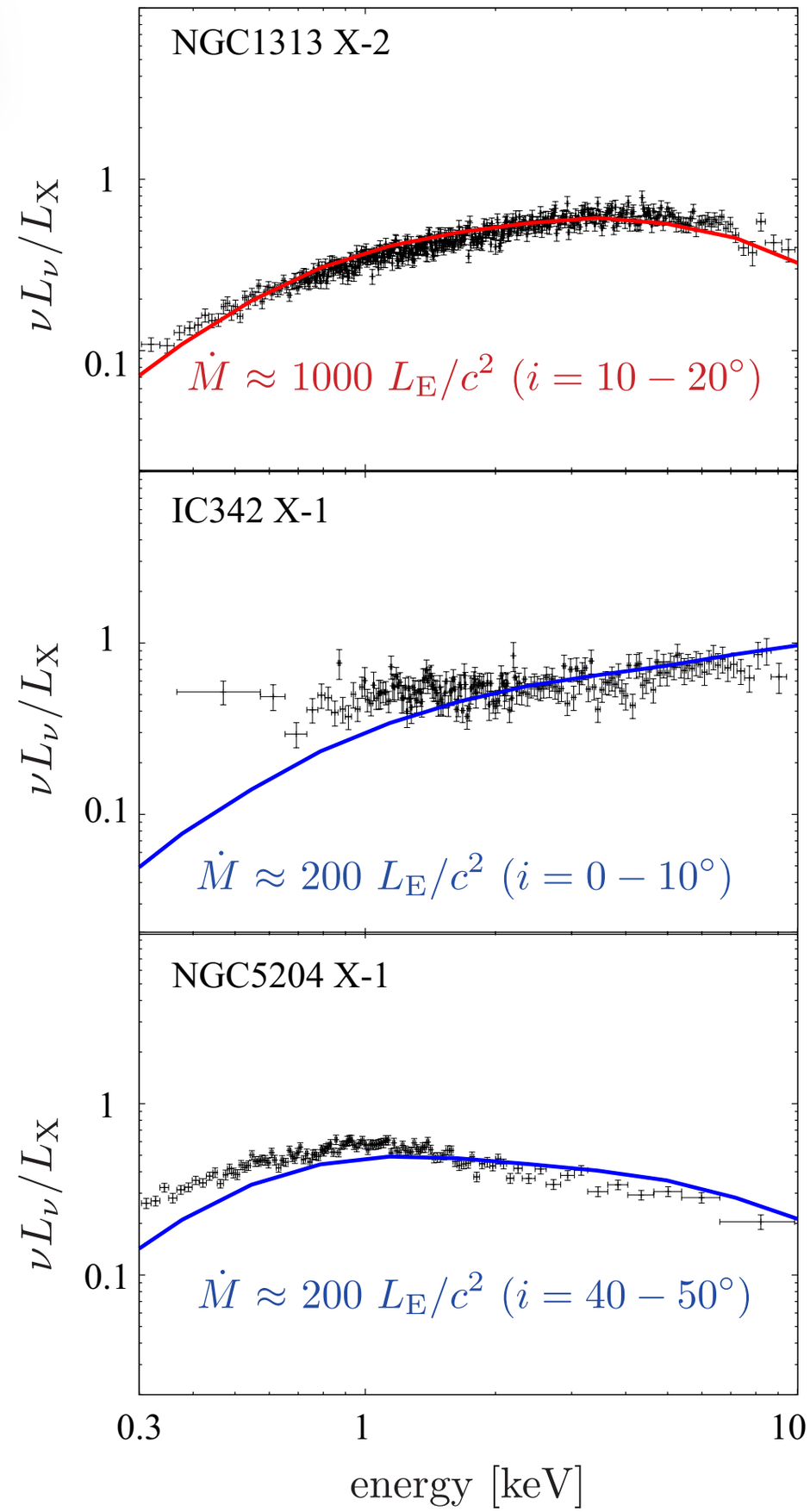
- hot coronal inflows upscatter the photons (i.e., inverse-Compton scattering).
- cool coronal outflows downscatter the photons (i.e., Compton scattering)

Comparison with ULXs

- colored curves: calculated spectra
- black points: XMM-Newton Data corrected for absorption (provided by Dr. Gladstone)

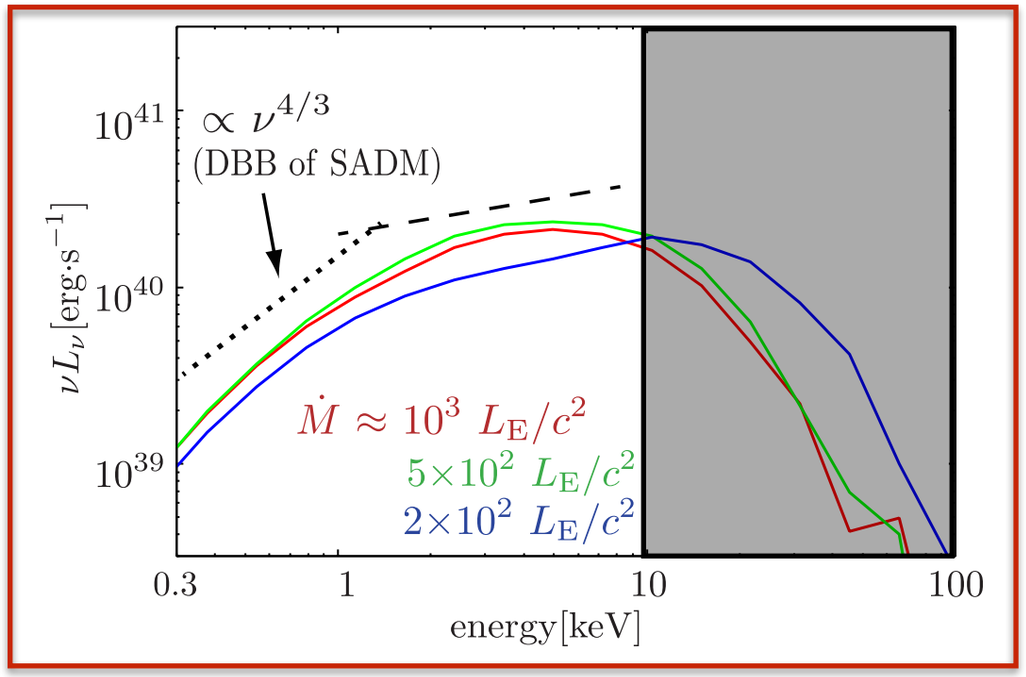
Calculated SEDs are similar to those of ULXs!
(rollover at 5keV, power-low shape)

However, the soft excess are not reproduced in our simulations, because the emission from $\sqrt{x^2+y^2} \geq 100 r_{\rm s}$ is too weak to significantly contribute to the SEDs.
<— Larger simulation box containing larger outflowing photosphere may solve this problem. And/or the effects of the magnetic dissipation may be important.



A little more about the spectral state of ULXs

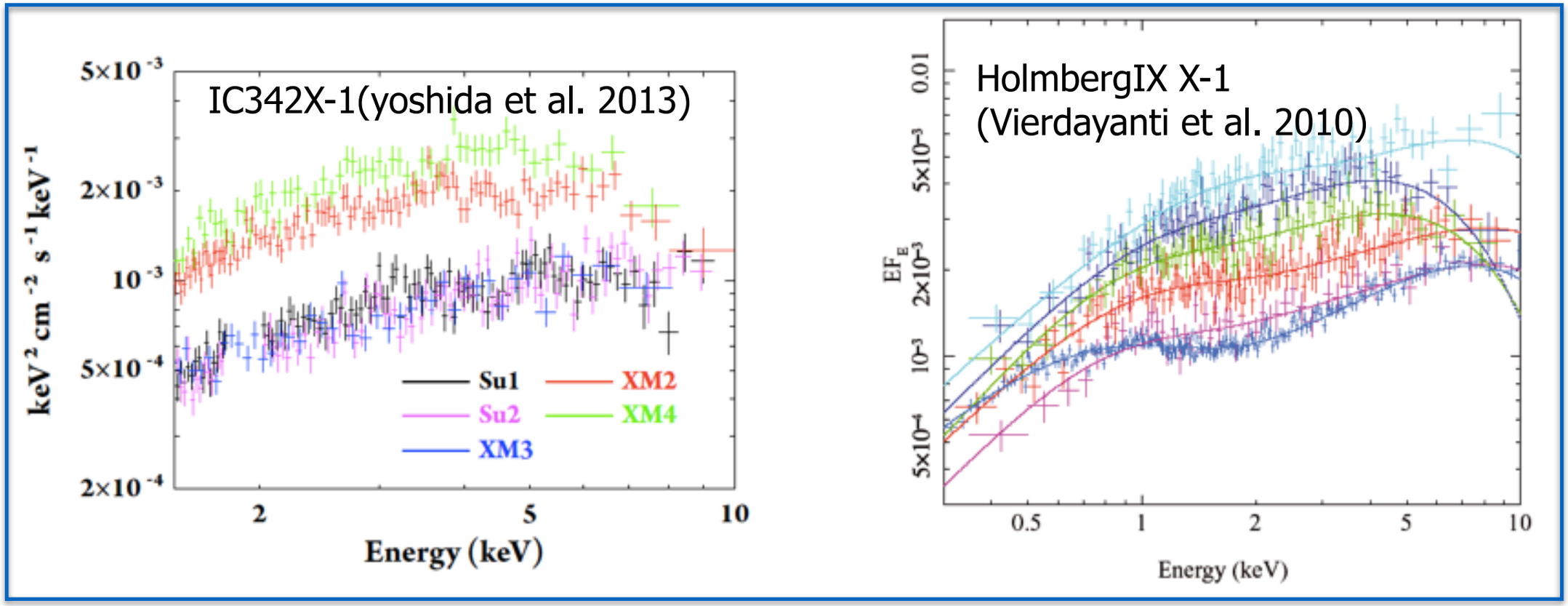
our result



- Variability of SEDs of soft state and dim hard state seems to be explained by our numerical model.

- Bright hard state (cyan) is , however, hard to be explained by our model. **We need more sophisticated theoretical models!**

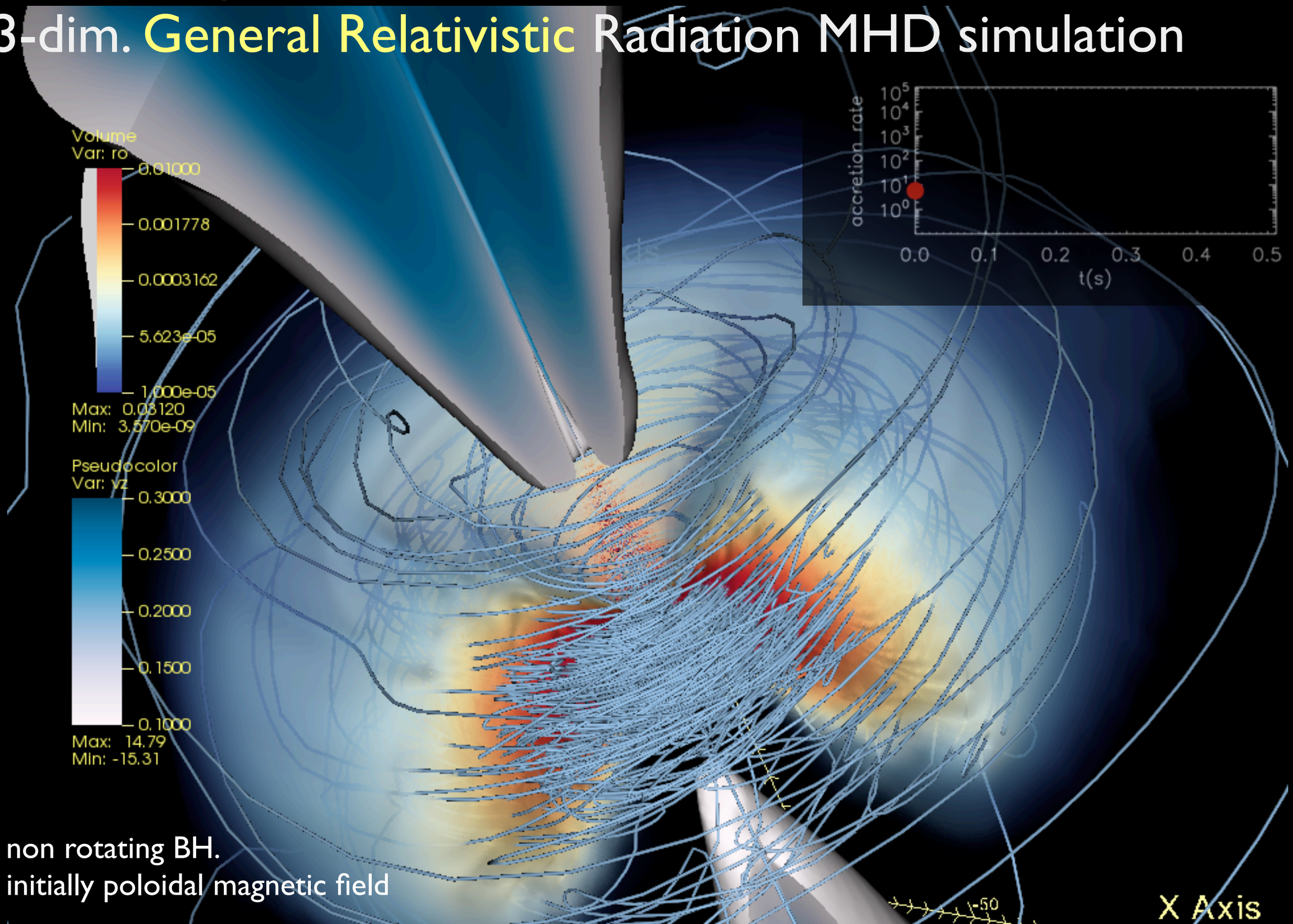
observation



(高橋博之さんのスライドより)

Second Topic: Where is the hot corona formed

3-dim. General Relativistic Radiation MHD simulation

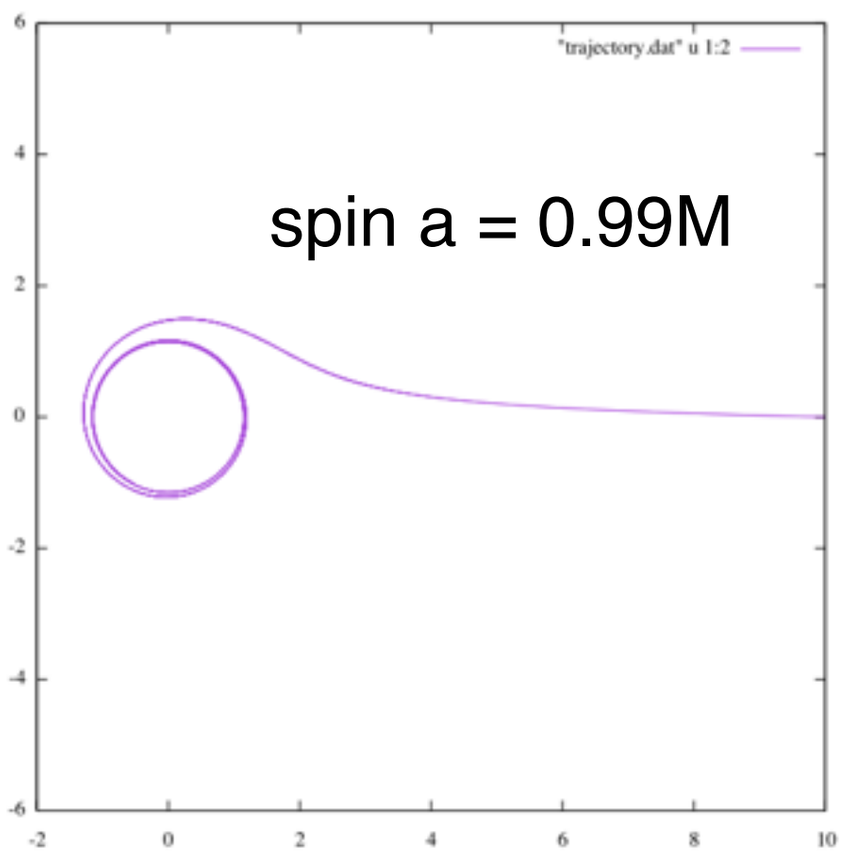


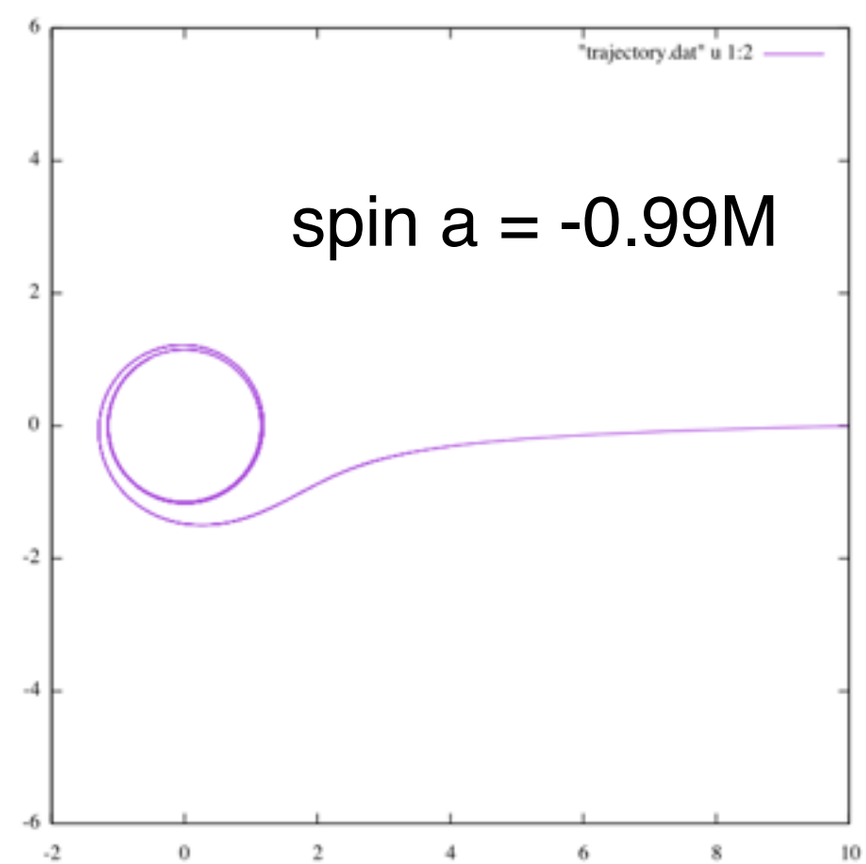
non rotating BH.
initially poloidal magnetic field

Development of GR radiative transfer code

- The accumulation of the poloidal magnetic fields threading the spinning BH results in the formation of the hot corona in the vicinity of the BH. (Takahashi et al. in prep.)

- I am now developing the GR radiative transfer code to calculate the more sophisticated SEDs of black hole accretion flows!

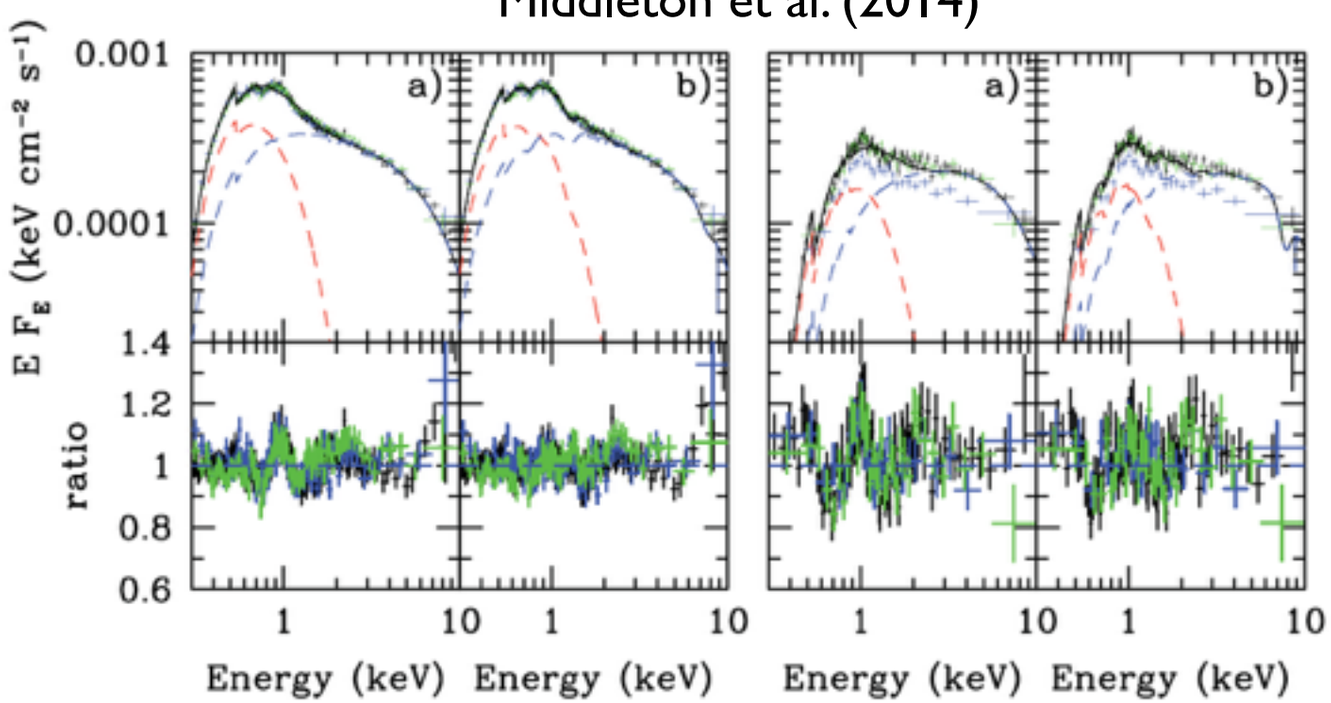




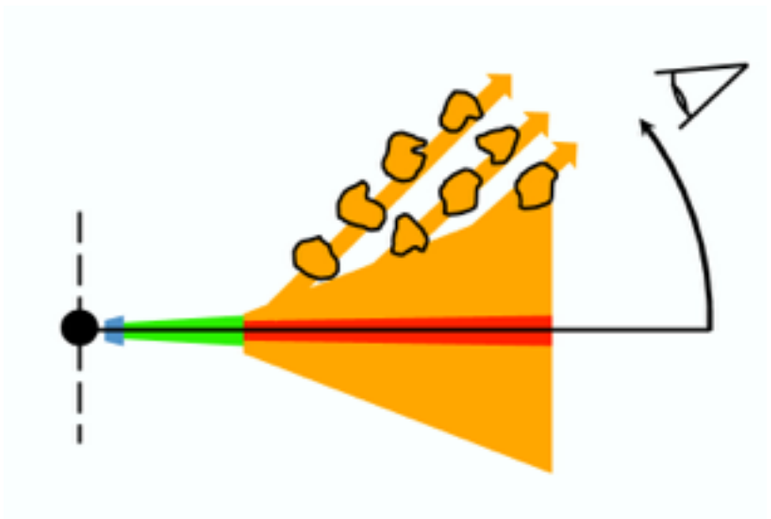
Discovery of Absorption Line in ULXs?

- Middleton et al. (2014) reported discovery of a blue-shifted absorption line with v~0.1c in NGC 5408 X-1 and NGC6946 X-1, which may be the evidence of the outflow.
- These ULXs show soft X-ray spectra. This indicates that we observe this source with higher inclination angle.
- It is important to theoretically reveal the dependence of the absorption line on the viewing angle.

Middleton et al. (2014)



Middleton et al. (2011)

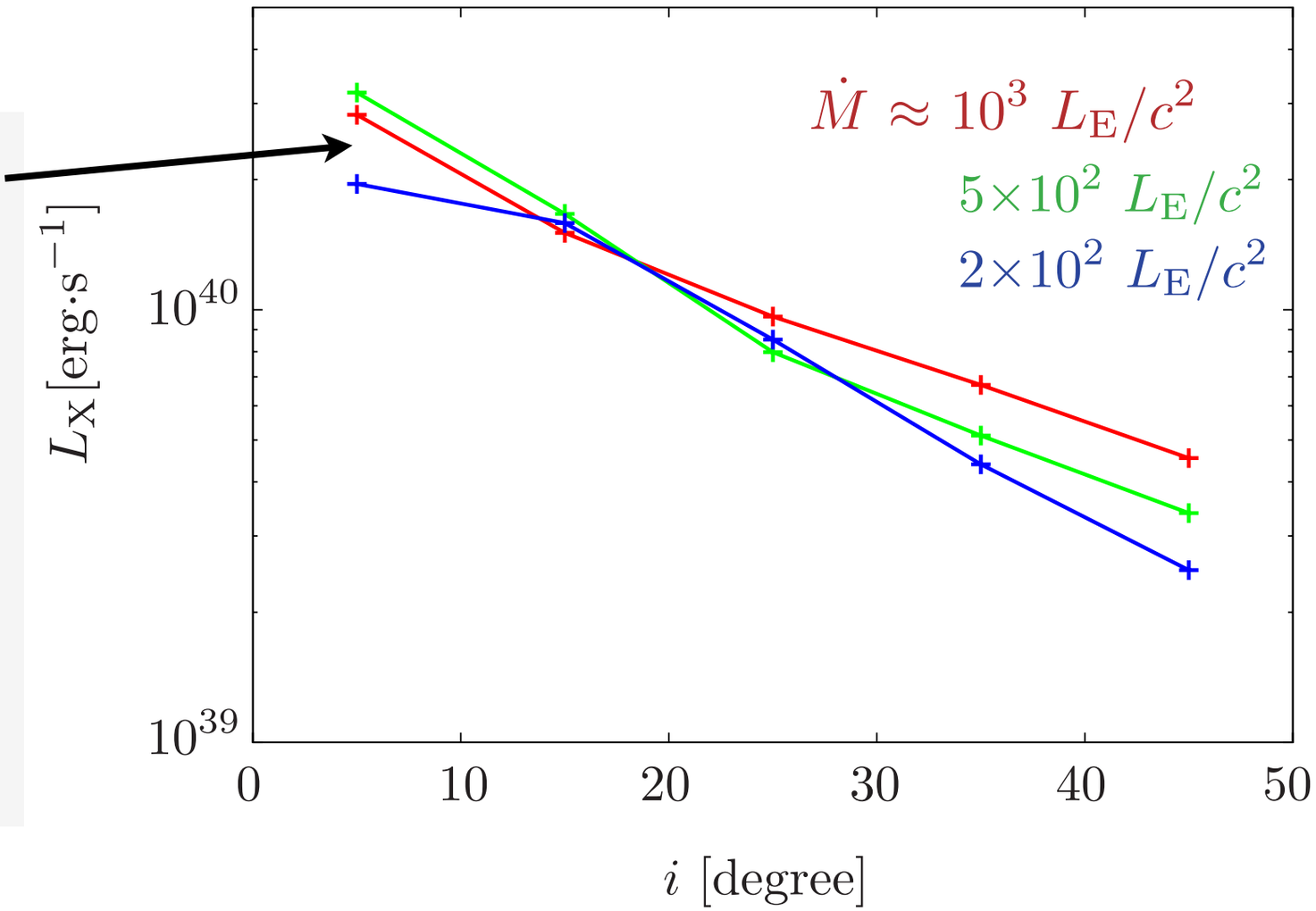


Summary

- The Compton effects are very important in super-critically accreting black holes.
- Coronal inflow is hot and upstaters the seed disk photons.. The upscattered photons are downscattered by the coronal cool outflow and the spectral rollover at ~5keV is formed.
- Super-critical accretion flows onto stellar-mass black holes can explain the spectral features of ULXs.
- The calculations including the effects of GR and line transfer are future work.
- I hopefully think we can apply our numerical methods to the studies of AGNs.

Dependence of Viewing Angle: (2) Luminosity

$L_{\rm X}$ for $\dot{M}\approx 10^3 L_{\rm E}/c^2$ is lower than that for $\dot{M}\approx 5\times 10^2 L_{\rm E}/c^2$, partly because more amount of photons are swallowed by BH and partly because $\tau_{\rm es}\gg 1$ along the funnel jet for $\dot{M}\approx 10^3 L_{\rm E}/c^2$



Isotropic luminosity increases when the viewing angle is smaller.

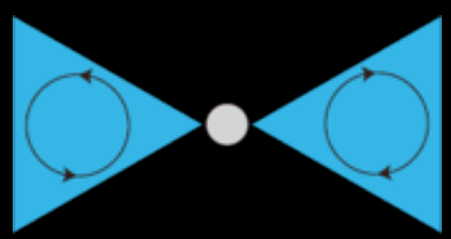
mildly collimated by the thick disk
and mildly beamed by the funnel jet!

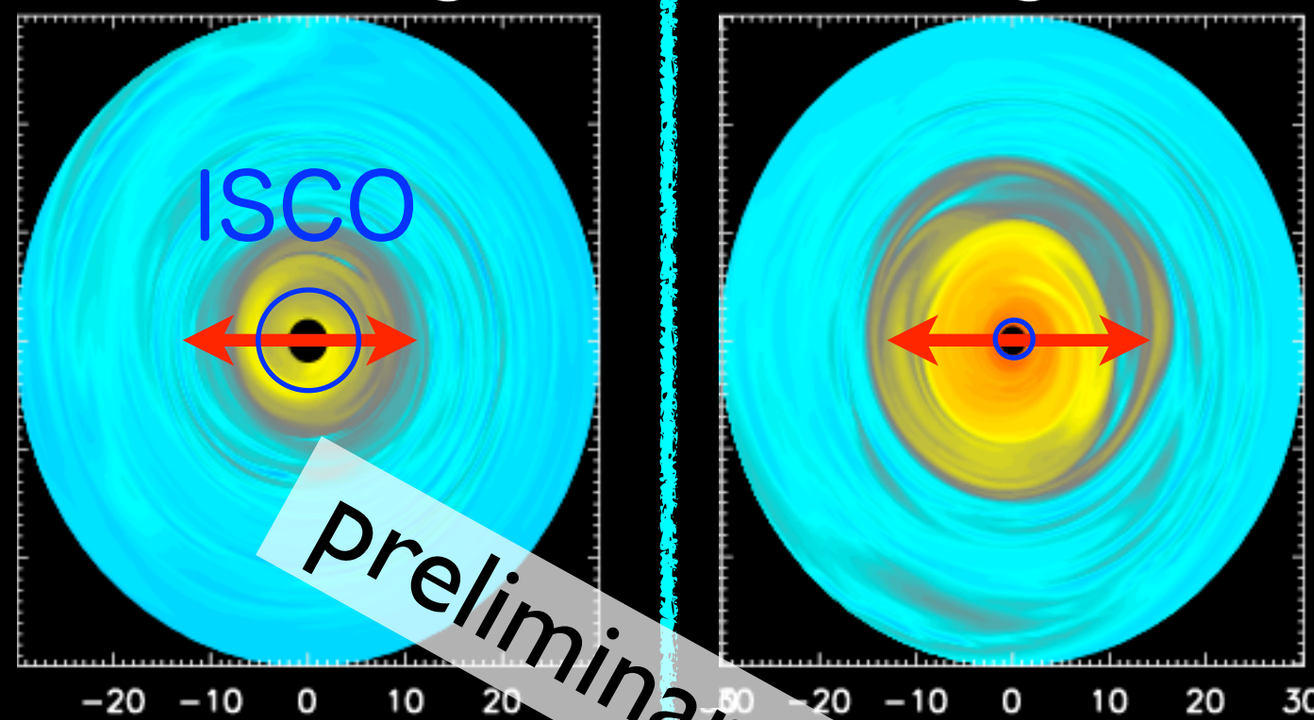
(高橋博之さんのスライドより)

gas temperature on the equatorial plane

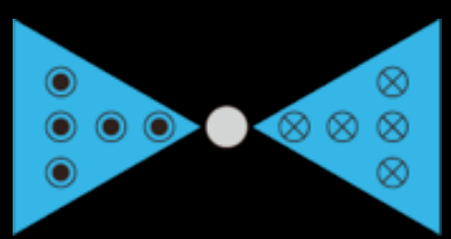
non-rotating BH | rotating BH(a=0.94)

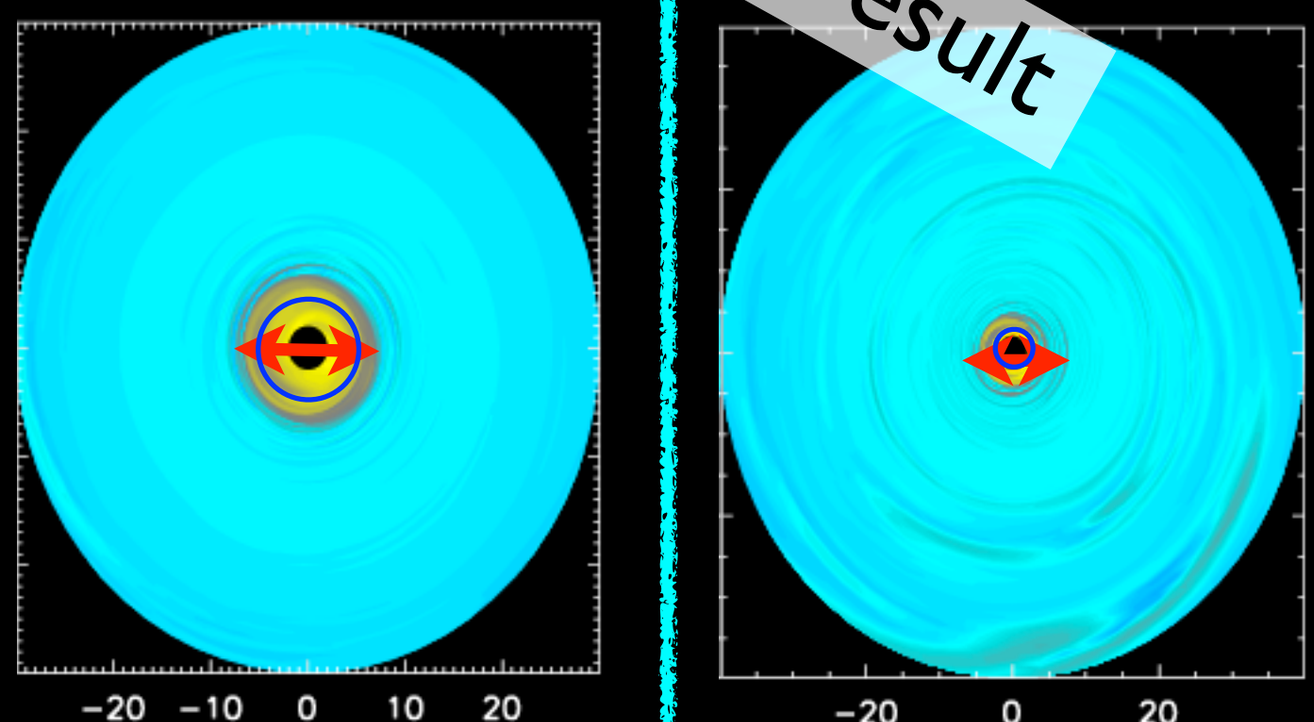
initially poloidal mag. field (r-θ)





initially toroidal mag. field (ϕ)





preliminary result

high temp. region

Tg >> Tr

low temp. region (in LTE

Tg = Tr

temperature inside the disk

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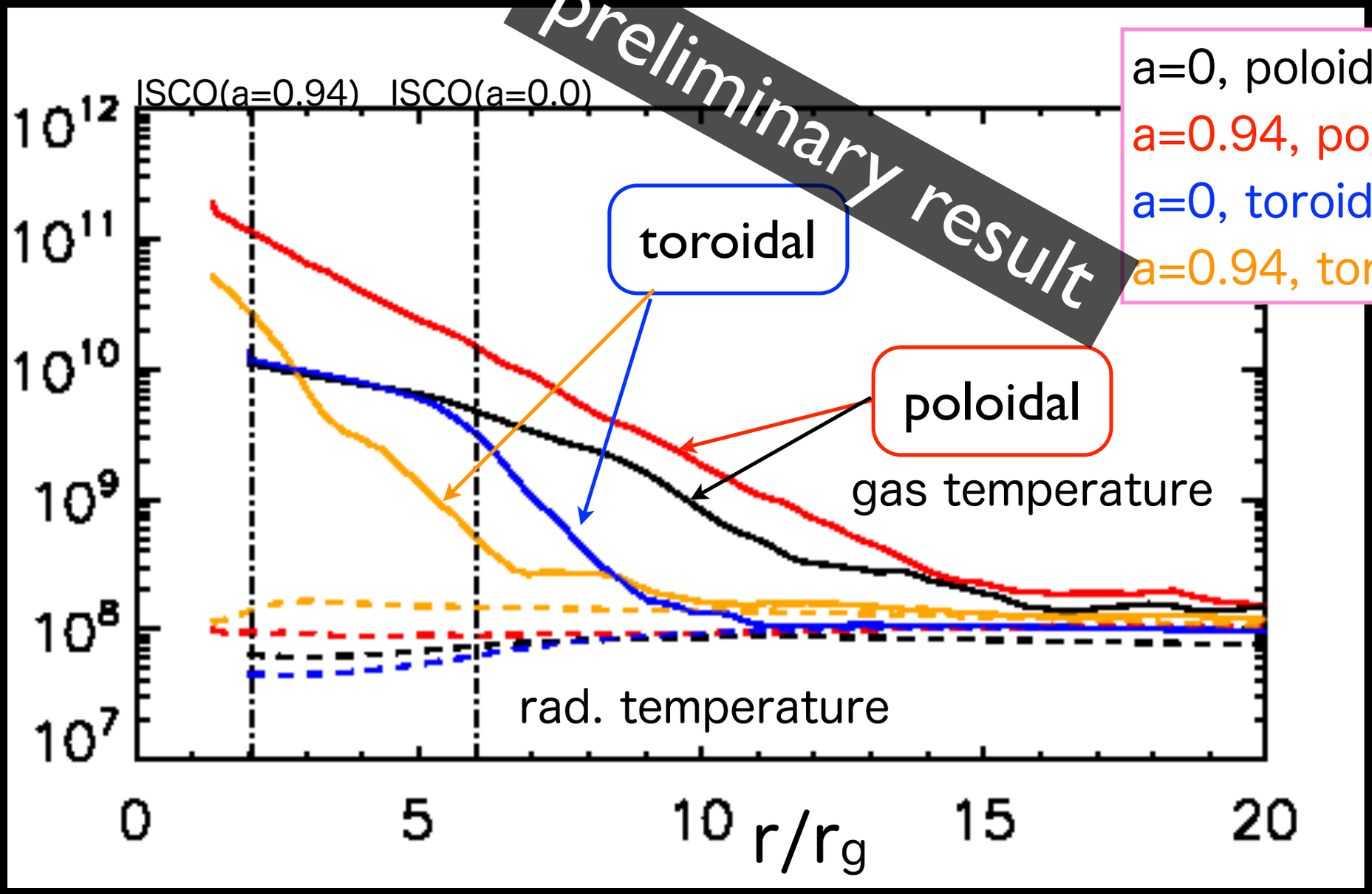

The gas is overheated near BH in all model.

The deviation starts at a larger radius for the poloidal model than the toroidal model.

The deviation starts from the radius (slightly) larger than the ISCO.