Hot Spine and Compton-Cooled Sheath Structure of Radiation MHD Jet:

Observational Feature of Super-Eddington Black Hole Accretion Flow and Outflow

Tomohisa KAWASHIMA (Shanghai Astronomical Observatory)

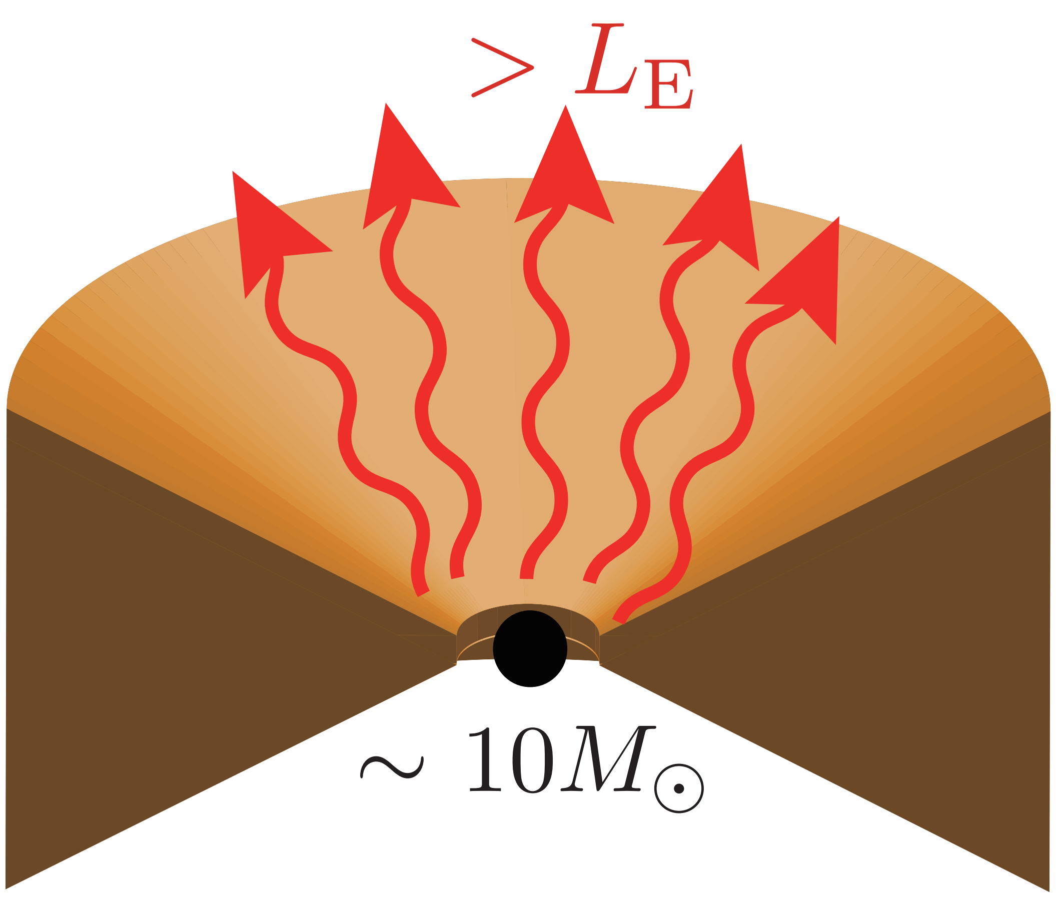
Ken OHSUGA (National Astronomical Observatory of Japan)
Shin MINESHIGE (Kyoto University)
Ryoji MATSUMOTO (Chiba University)

Super-Eddington 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：

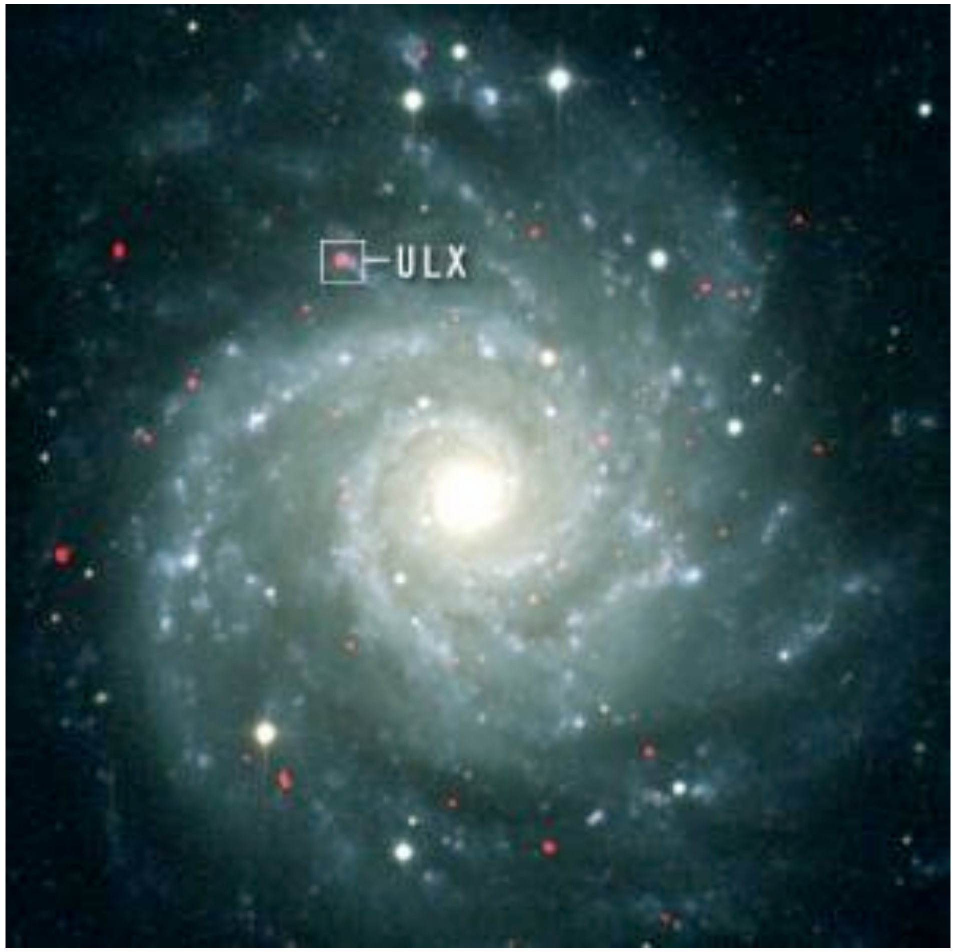
  powerful jet sources (SS433, S26)
  Narrow Line Seyfert I, OVV quasars,
  microquasar (GRS1915+105),

  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



http://www.sciencedaily.com

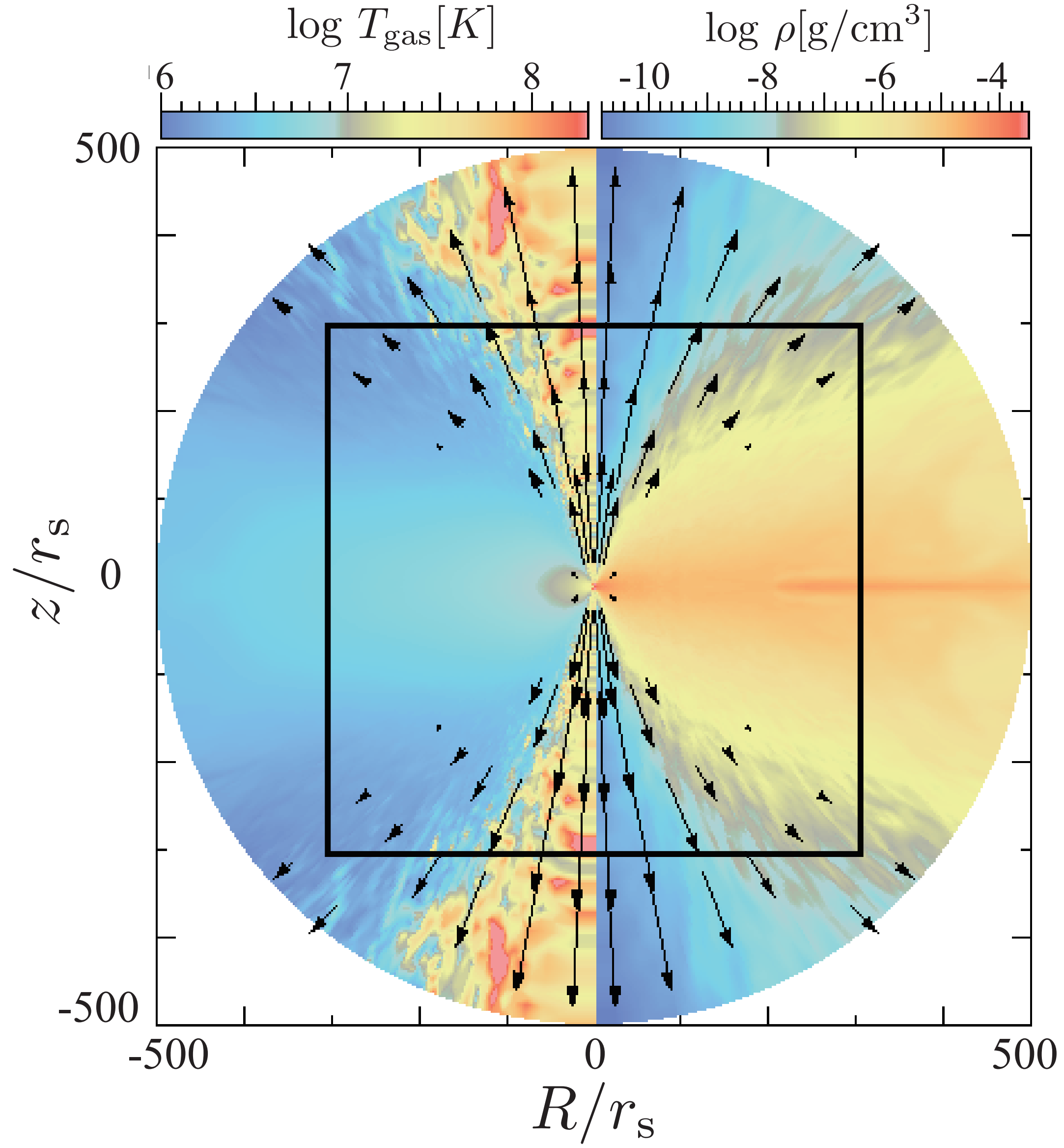
(A)subcritically accreting intermediate mass BH?
or
(B)supercritically accreting stellar-mass BH?

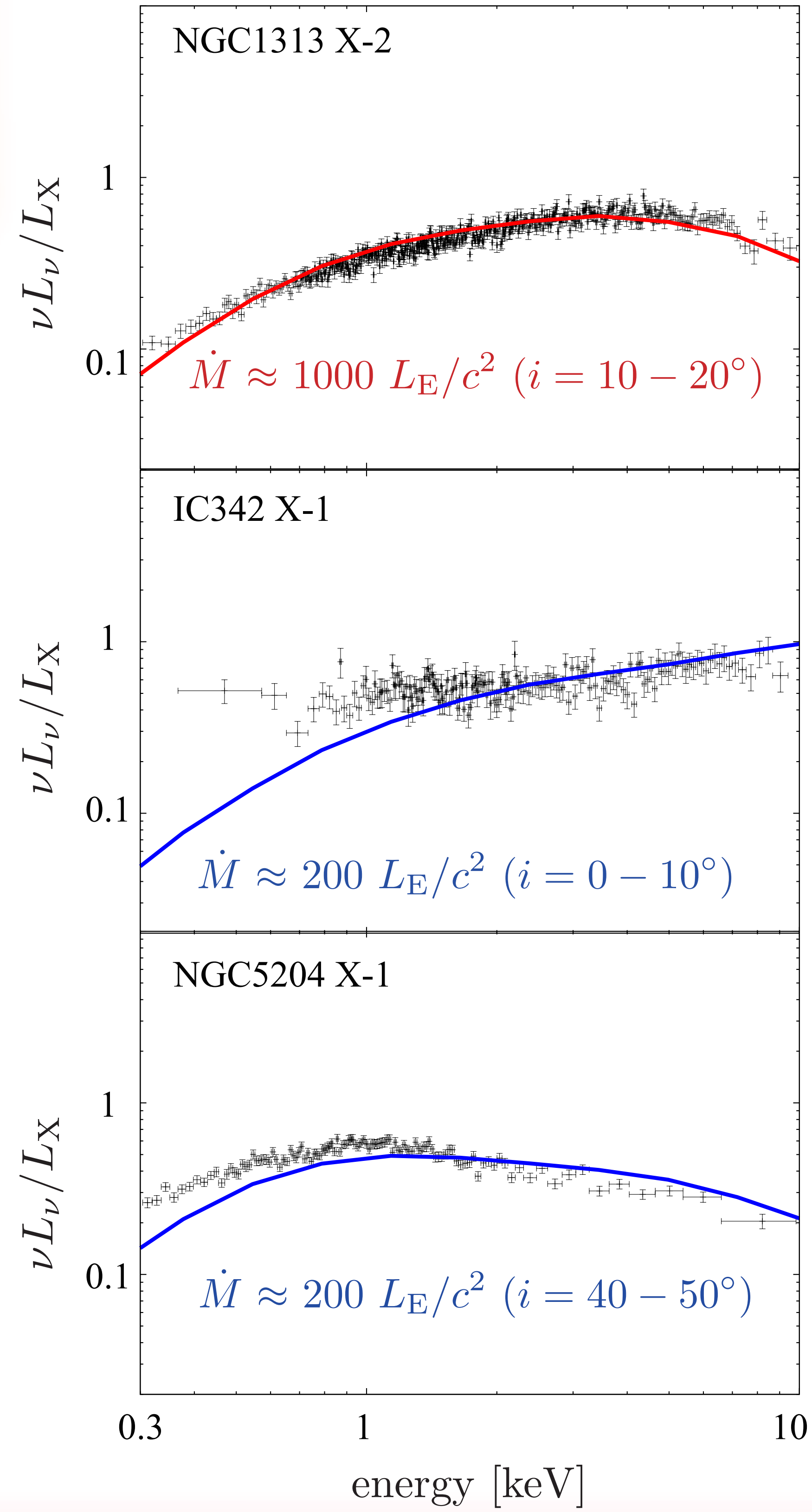
This problem remains an open issue.

The other problem:
ULXs show the spectral features different with galactic BHCs nor AGNs.
---> The spectral studies are expected to be a key to understand ULXs.

Calculation of Spectra of Super-Eddington Accretion Flow based on Rad-HD simulation

(TK et al. 2012, ApJ)

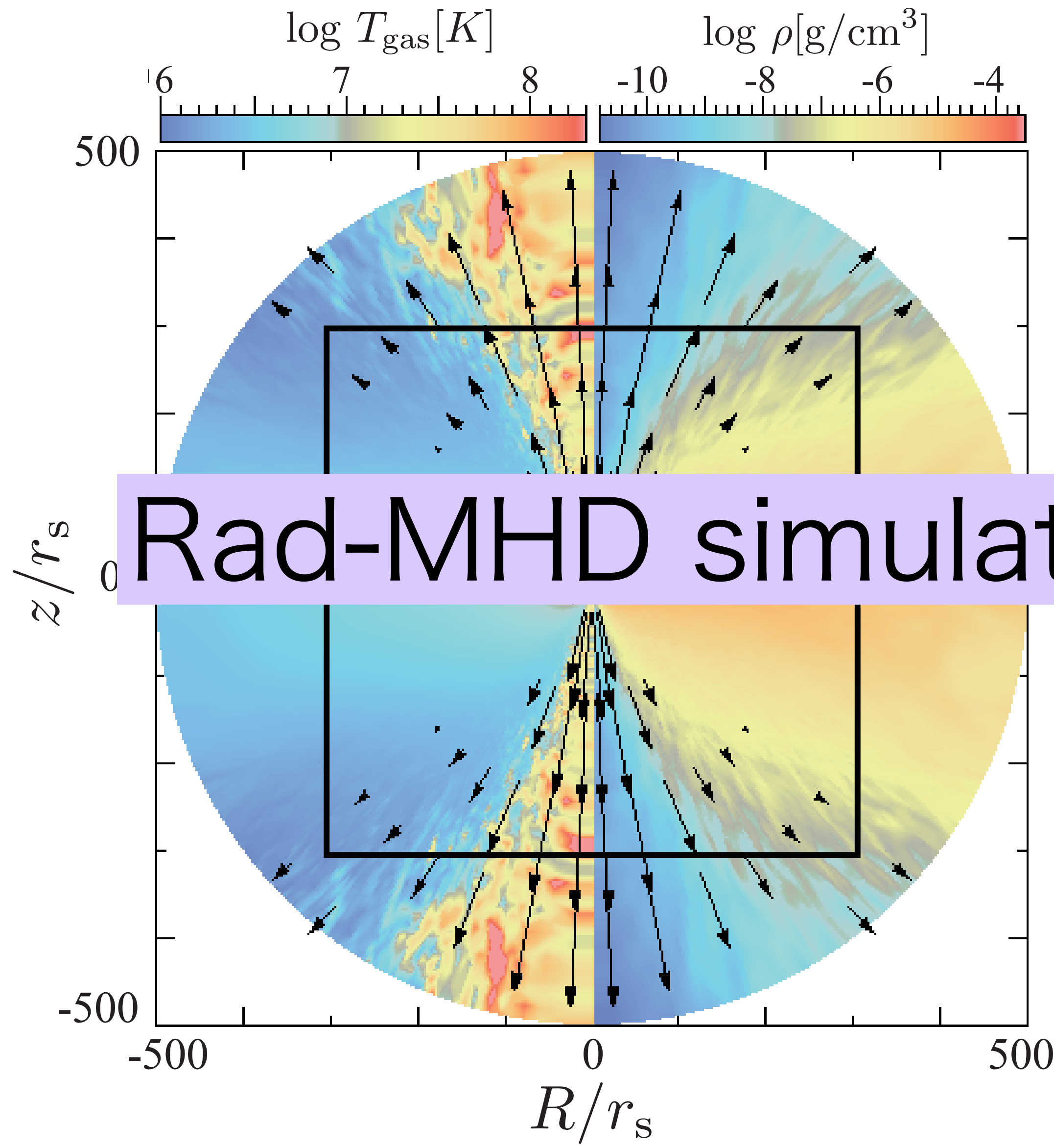




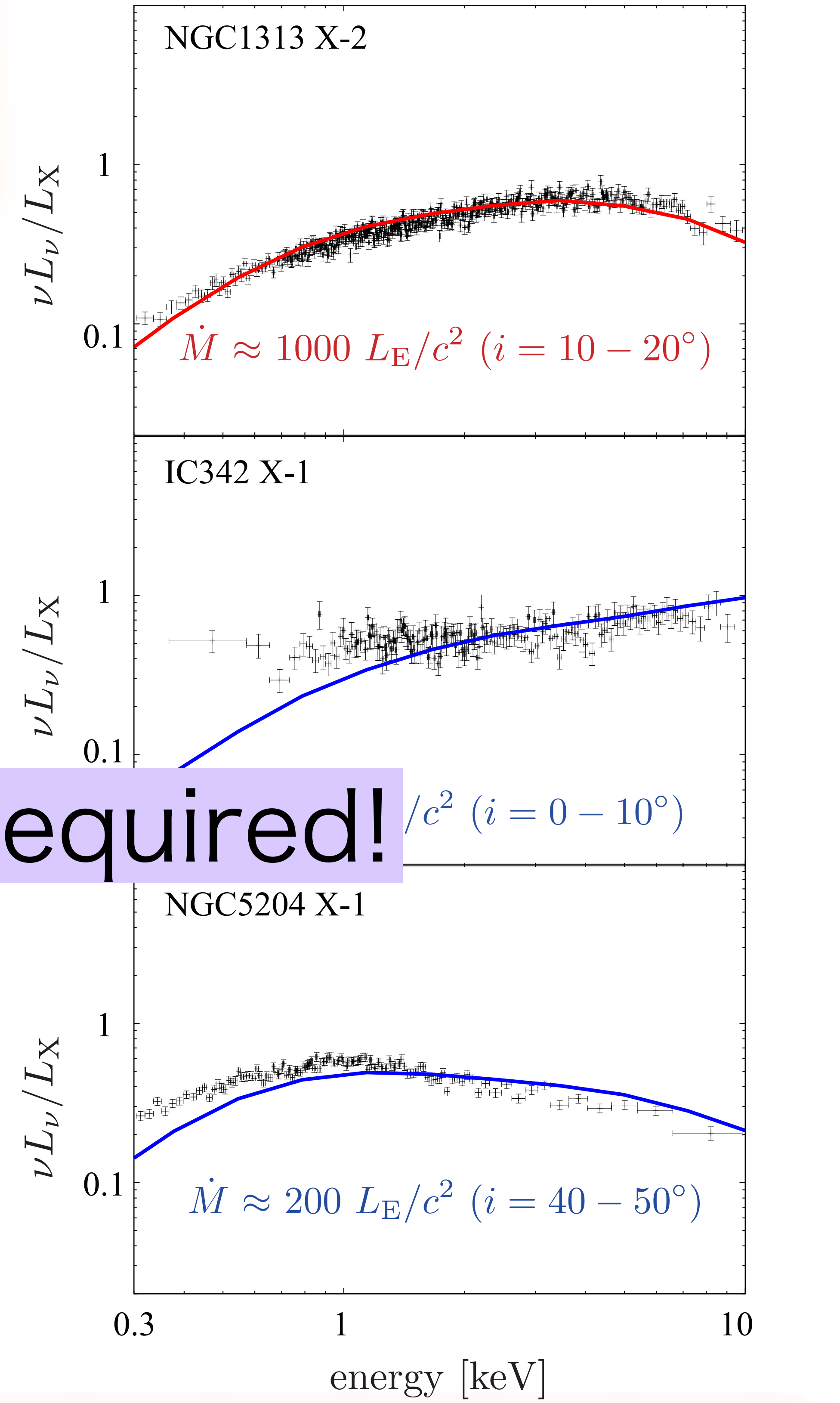
- We reproduced the roll-over around 5keV and hard PL spectra!
- However, we could not reproduce the soft excess around 1keV... because the wind is too cool. <= magnetic dissipation over the disk can increase the temperature in the wind?

Calculation of Spectra of Super-Eddington Accretion Flow based on Rad-HD simulation

(TK et al. 2012, ApJ)



Rad-MHD simulation is required!



- We reproduced the roll-over around 5keV and hard PL spectra!
- However, we could not reproduce the soft excess around 1keV... because the wind is too cool. <= magnetic dissipation over the disk can increase the temperature in the wind?

Rad-MHD Equations

Equations are the same as those of K. Ohsuga's work
except we take into account the effect of Compton cooling/heating.

- the continuity equation: $$\frac{\partial \rho}{\partial t} + \boldsymbol{\nabla}\cdot(\rho \boldsymbol{v}) = 0$$
- the equation of motion: $$\frac{\partial (\rho \boldsymbol{v})}{\partial t} + \boldsymbol{\nabla}\cdot\left(\rho \boldsymbol{v}\boldsymbol{v} - \frac{\boldsymbol{B}\boldsymbol{B}}{4\pi}\right) = -\boldsymbol{\nabla}\left(p + \frac{|\boldsymbol{B}|^2}{8\pi}\right) + \frac{\chi}{c}\boldsymbol{F}_0 - \rho \boldsymbol{\nabla}\Psi$$
- the energy equation of gas: $$\frac{\partial e}{\partial t} + \boldsymbol{\nabla}\cdot(e\boldsymbol{v}) = -p\boldsymbol{\nabla}\cdot\boldsymbol{v} + \frac{4\pi}{c^2}\eta J^2 - 4\pi\kappa B + c\kappa E_0 \boxed{- \Gamma_{\mathrm{Comp}}}$$
- the energy equation of radiation: $$\frac{\partial E_0}{\partial t} + \boldsymbol{\nabla}\cdot(E_0\boldsymbol{v}) = -\boldsymbol{\nabla}\cdot\boldsymbol{F}_0 - \mathbf{P}_0 : \boldsymbol{\nabla}\boldsymbol{v} + 4\pi\kappa B - c\kappa E_0 \boxed{+ \Gamma_{\mathrm{Comp}}}$$

  Here, Compton cooling/heating term is: $$\boxed{\Gamma_{\mathrm{Comp}} = 4\sigma_{\mathrm{T}} c \frac{k_{\mathrm{B}}(T_{\mathrm{gas}} - T_{\mathrm{rad}})}{m_{\mathrm{e}} c^2}\left(\frac{\rho}{m_{\mathrm{p}}}\right) E_0}$$
- the induction equation: $$\frac{\partial \boldsymbol{B}}{\partial t} = \boldsymbol{\nabla}\times\left(\boldsymbol{v}\times\boldsymbol{B} - \frac{4\pi}{c}\eta \boldsymbol{J}\right)$$

FLD approximation is employed to close the energy equation of radiation.

simulation model

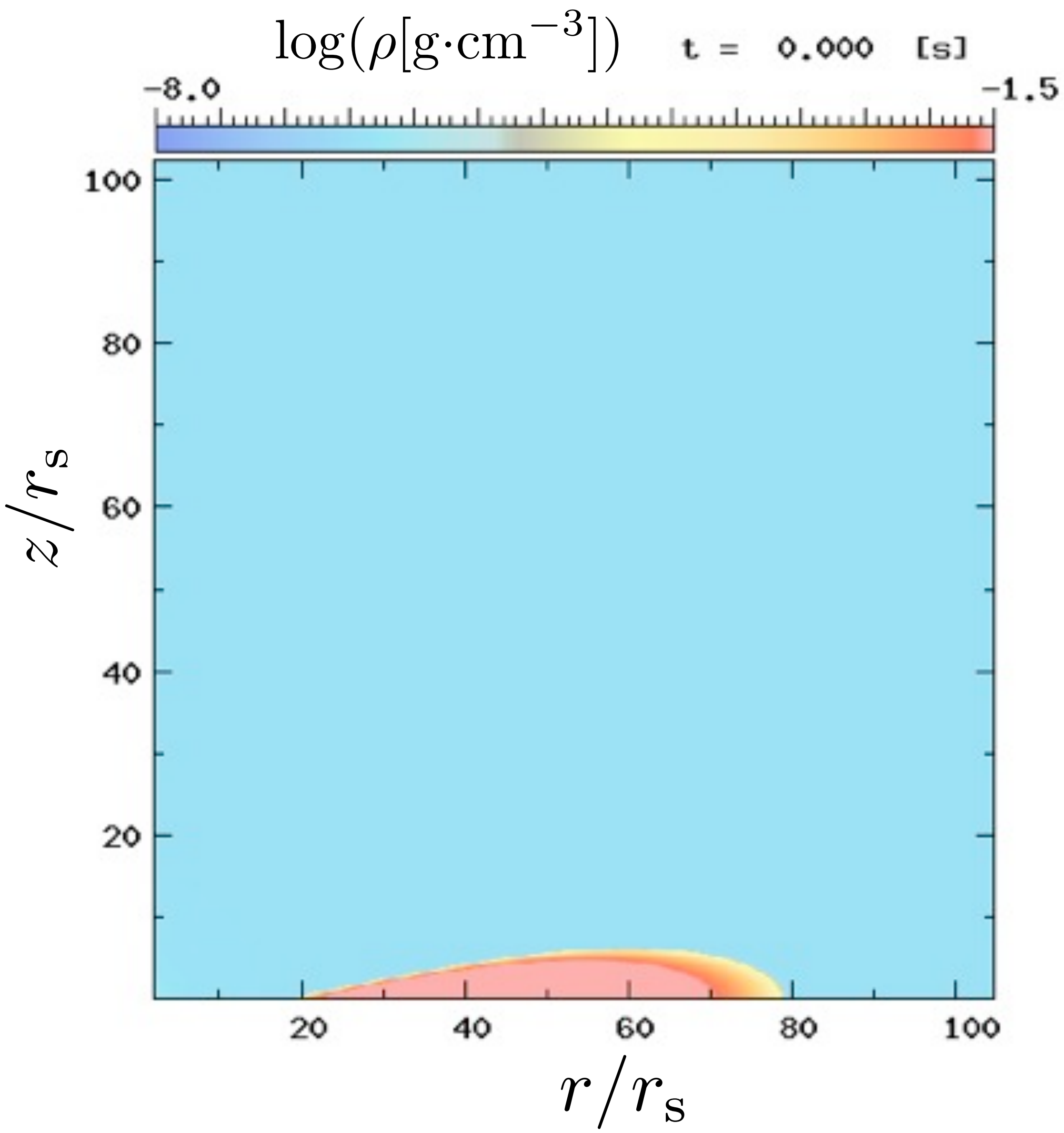
- **Axisymmetric 2D simulation with Cylindrical Coordinate** $(r, (\varphi), z)$
- **Simulation Domain:** $2R_\mathrm{s} \le r \le 105R_\mathrm{s}$ **,** $0 \le z \le 103R_\mathrm{s}$
- **Number of Grid points:** $(N_r, N_z) = (512, 512)$

- Torus -

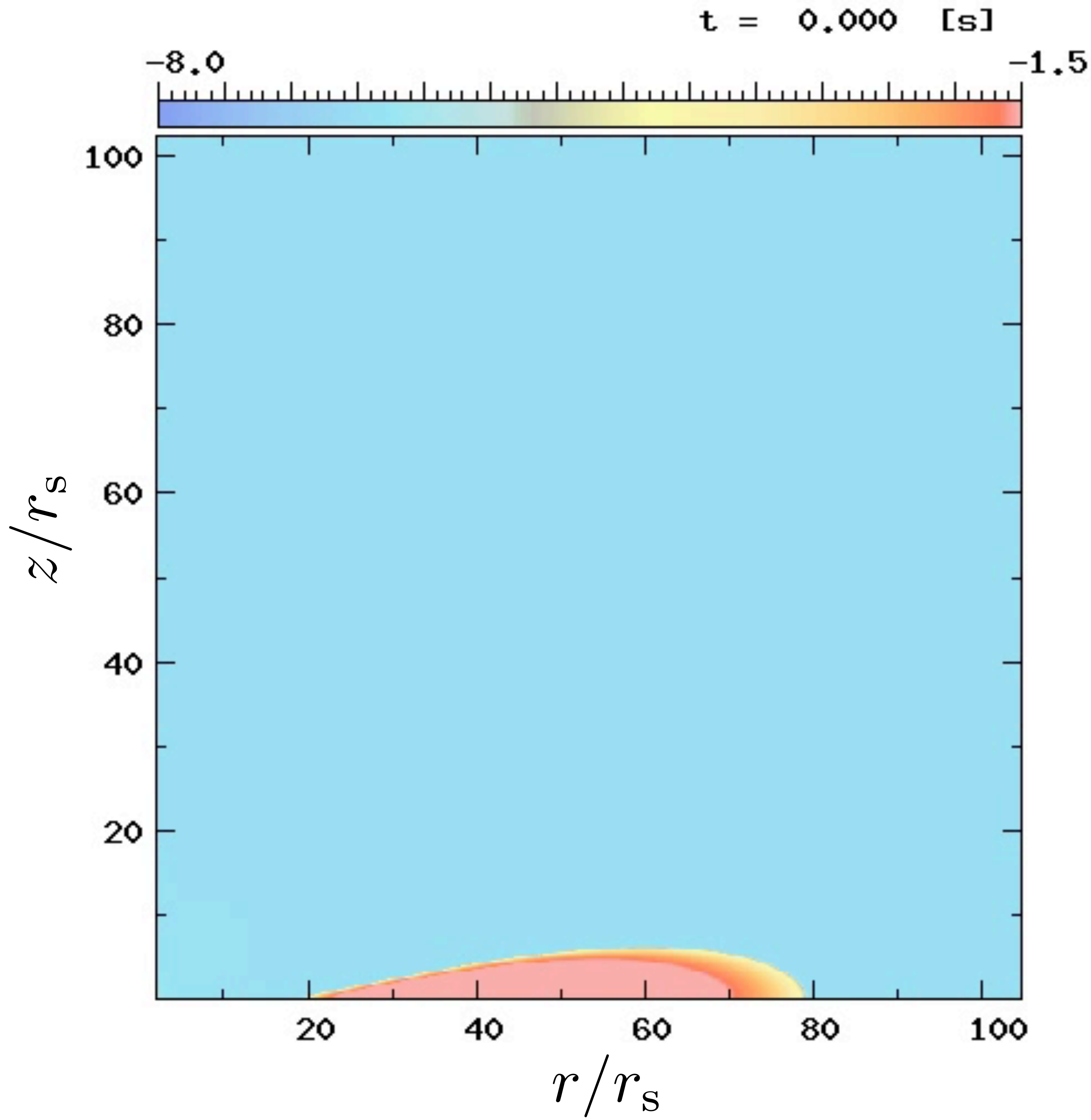
- The initial rotating torus in hydrostatic balance is set in the simulation domain.
- They set dipole magnetic field ($B_\varphi = 0$) inside the torus. The plasma-β is set to be 100.

- Corona -

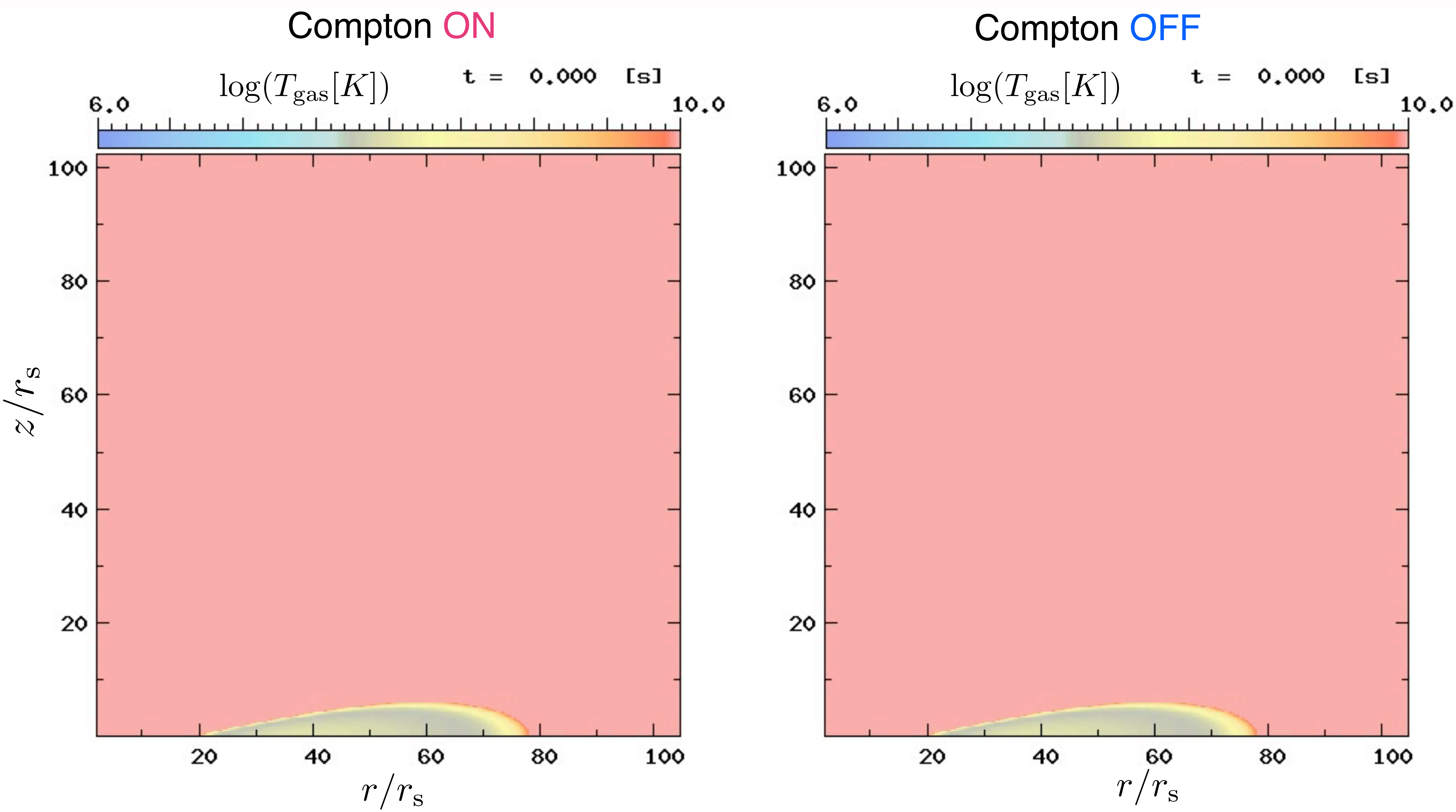
- The initial torus is embedded in a non-rotating corona. The corona is initially in hydrostatic equilibrium.



Simulation Movie (ρ)



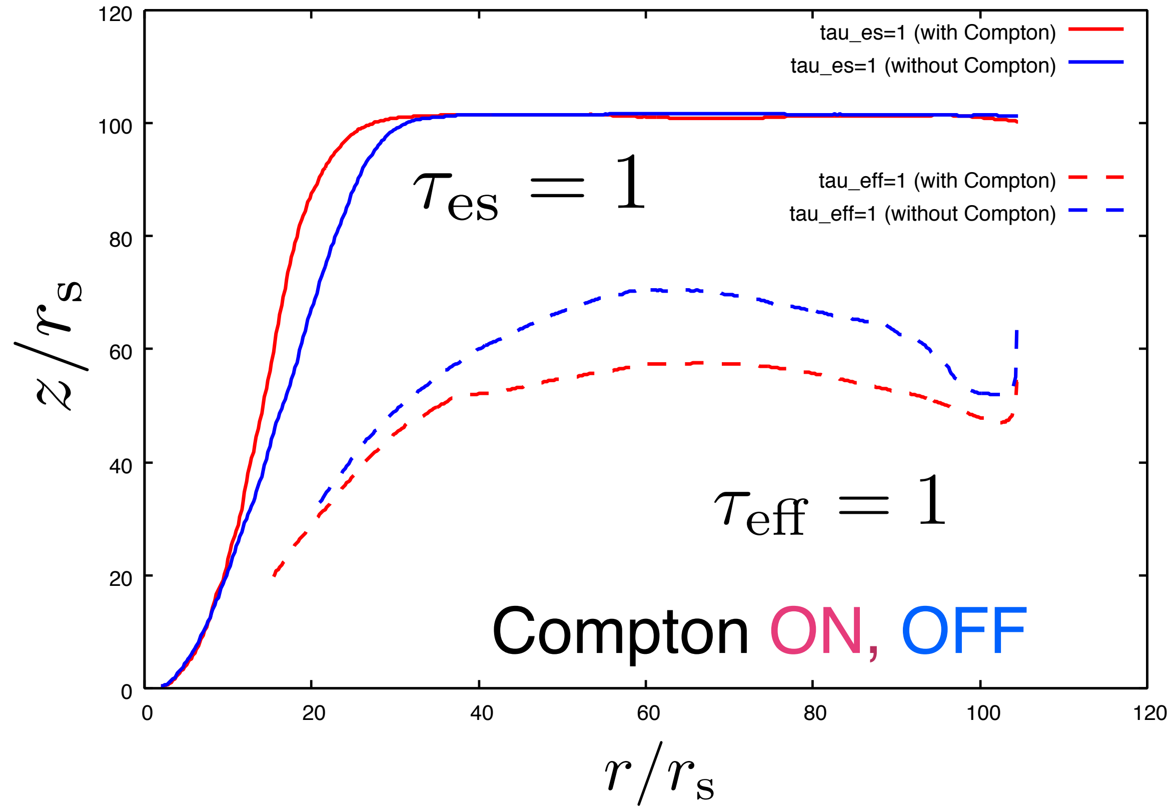
Effect of Compton Cooling on the Structure of the Jet and Wind

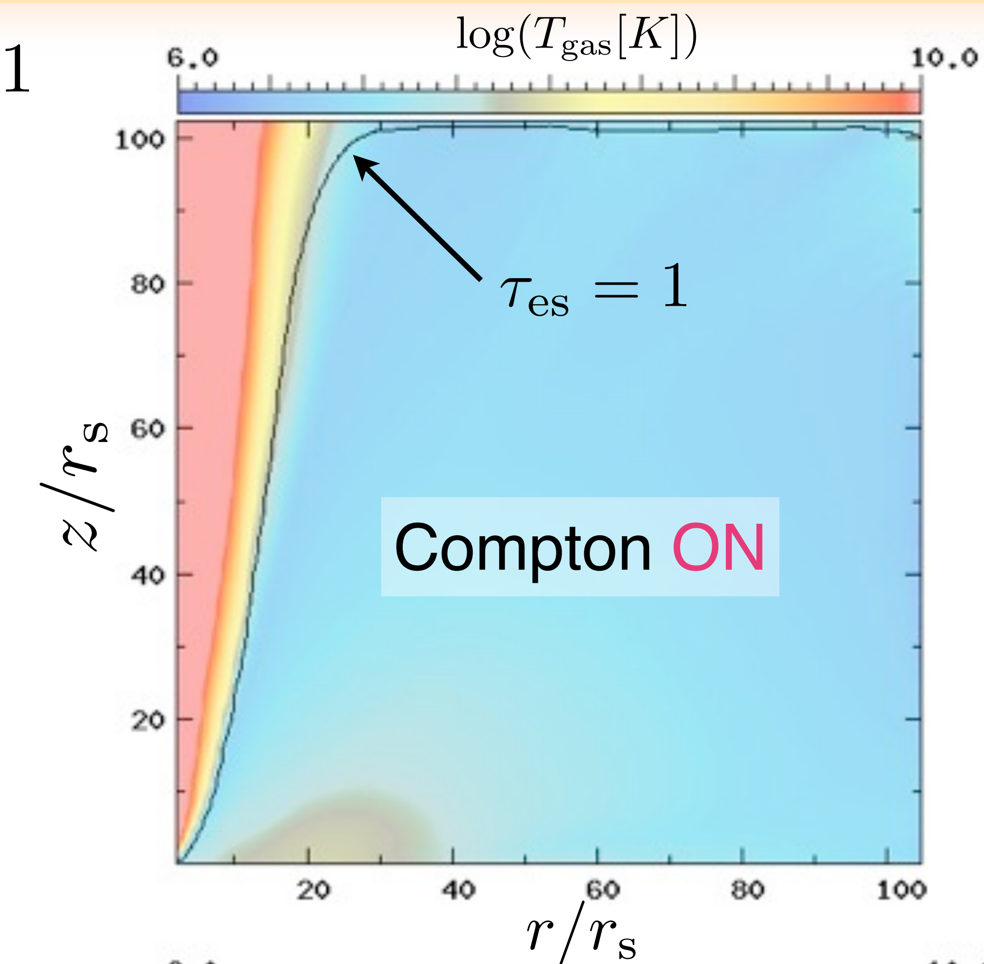


- The Sheath region of the jet and the wind is cooled through Compton scatterings.
- The jet is a little bit more collimated when the Compton cooling is taken into account.

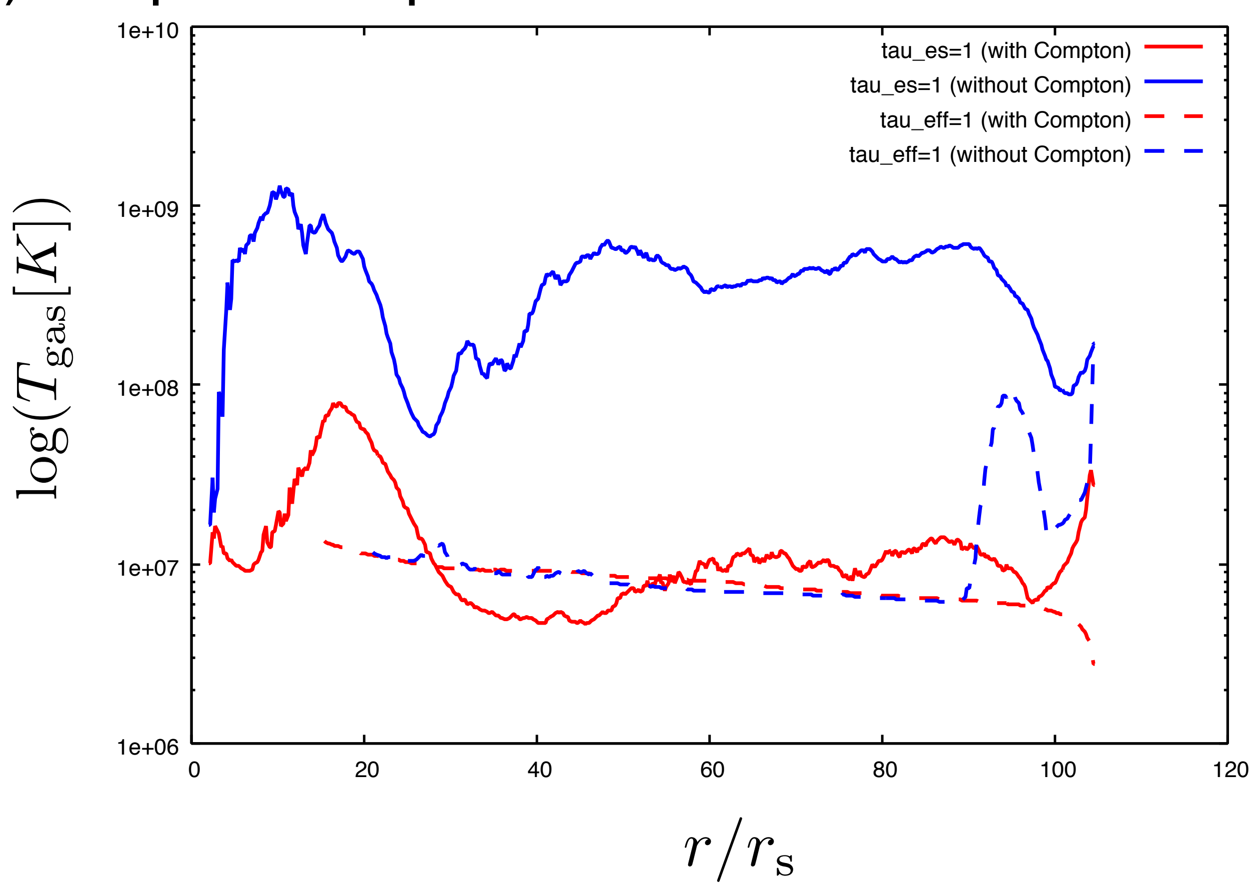
Temperature profile at the surface $\tau_{\rm es} = 1$

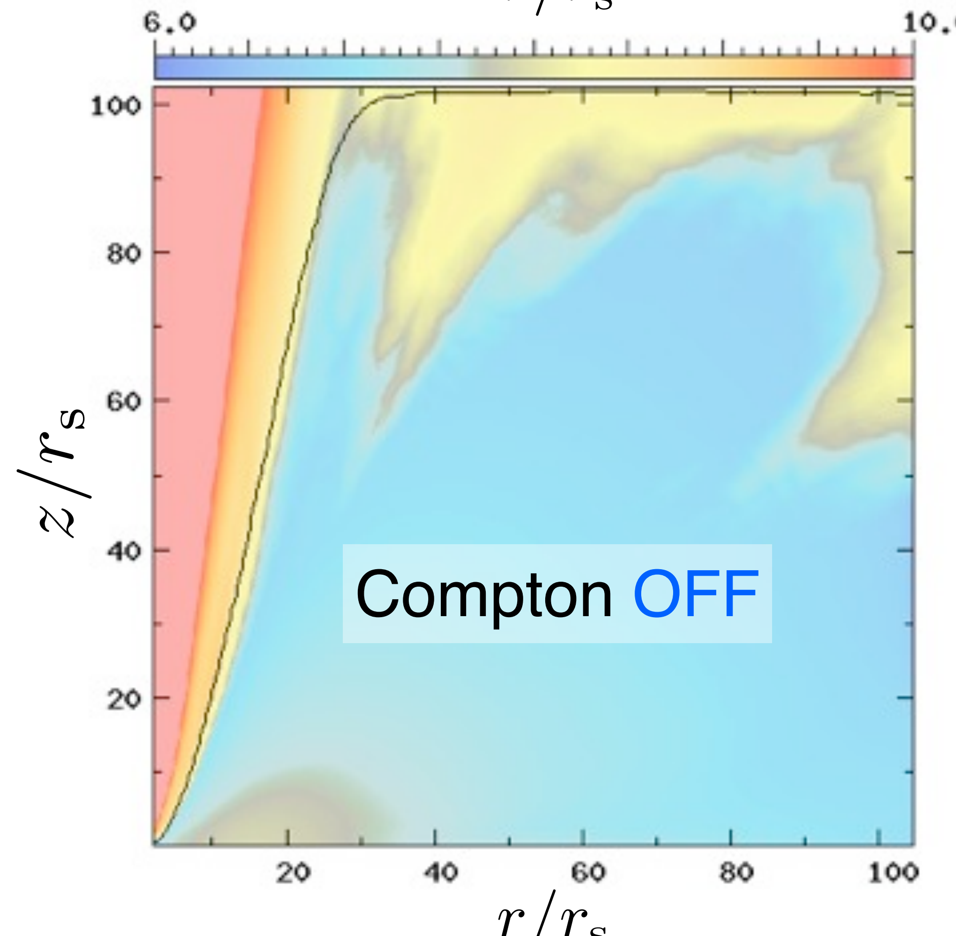
(1) position of the surface where $\tau_{\rm es} = 1$ and $\tau_{\rm eff} = 1$



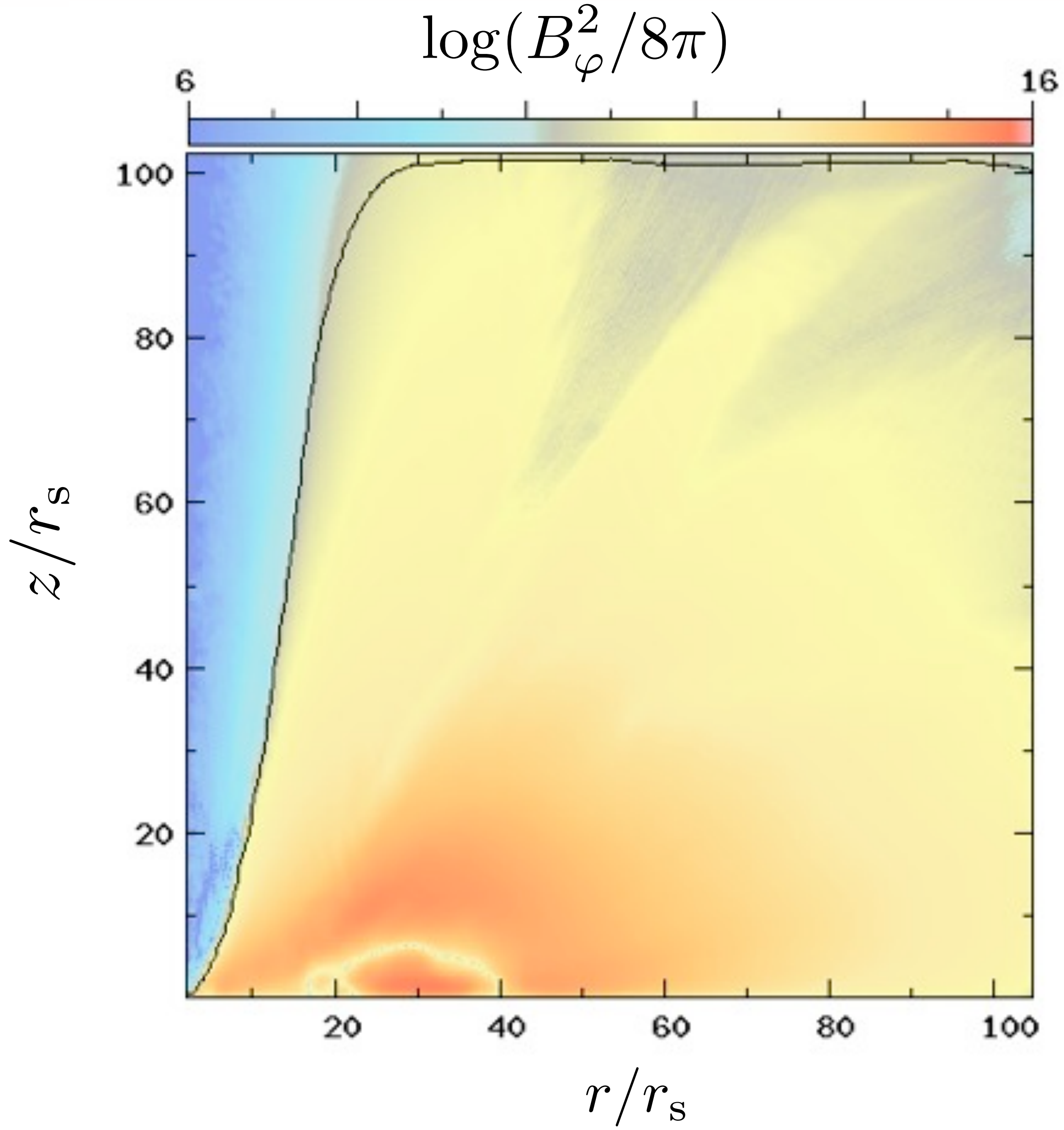


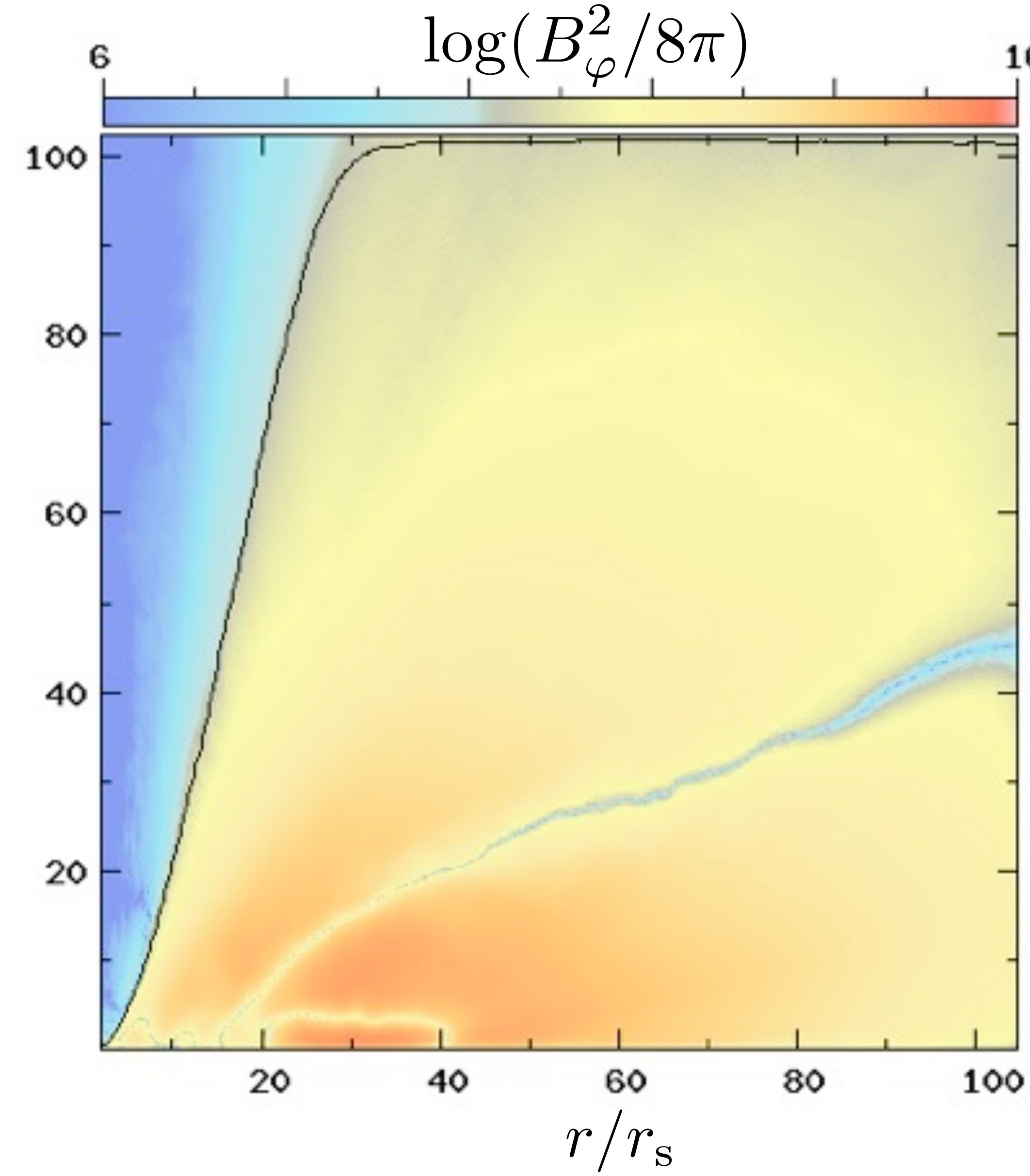
(2) temperature profile at $\tau_{\rm es} = 1$ and $\tau_{\rm eff} = 1$





Why the jet is a little bit become narrower?





- By the Efficient Compton Cooling, the disk shrinks.
- B_phi is amplified inside the disk => jet is well collimated!

Conclusion

- We performed axisymmetric 2D Rad-MHD simulation including Compton Cooling.

- Hot spine and Compton-Cooled sheath jet appears. We expect Compton-Cooled sheath jet will reproduce the spectral roll-over around 5 keV.

- The Compton-Cooled wind, which is a little hotter than that of Rad-HD simulation may reproduce the soft excess around 1keV observed in ULXs.

- The spectral calculation post-processing the result of Rad-MHD simulation remains as near future work.