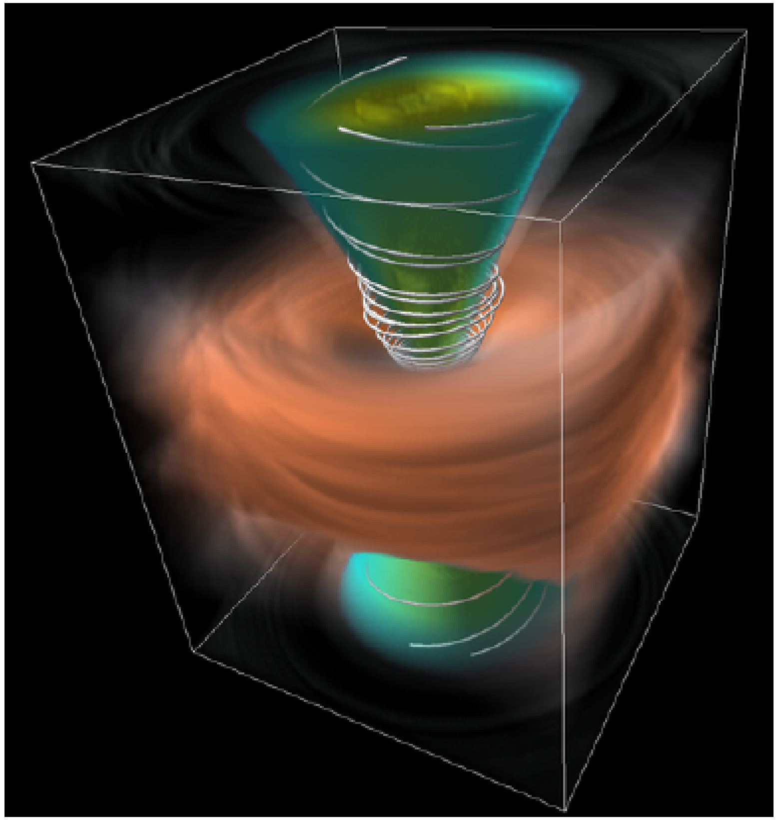
ULXs and Accretion Flow Models

Shin Mineshige (Kyoto) & Ken Ohsuga (NAOJ)



Magnetic tower jet
by RMHD simulation
(S. Takeuchi et al.)

Outline

- Introduction
  - Basics of supercritical (super-Eddington) accretion
  - Photon trapping and outflow
- Global radiation-hydrodynamic simulations
  - Significant radiation anisotropy
  - Outflow properties
- Model fits to ULXs & a microquasar
  - Spectral model
  - Spectral fits to ULXs & GRS1915+105
- Global radiation-magnetohydrodynamic simulations
  - Three different regimes of accretion flow
  - Magnetized, radiation driven jet

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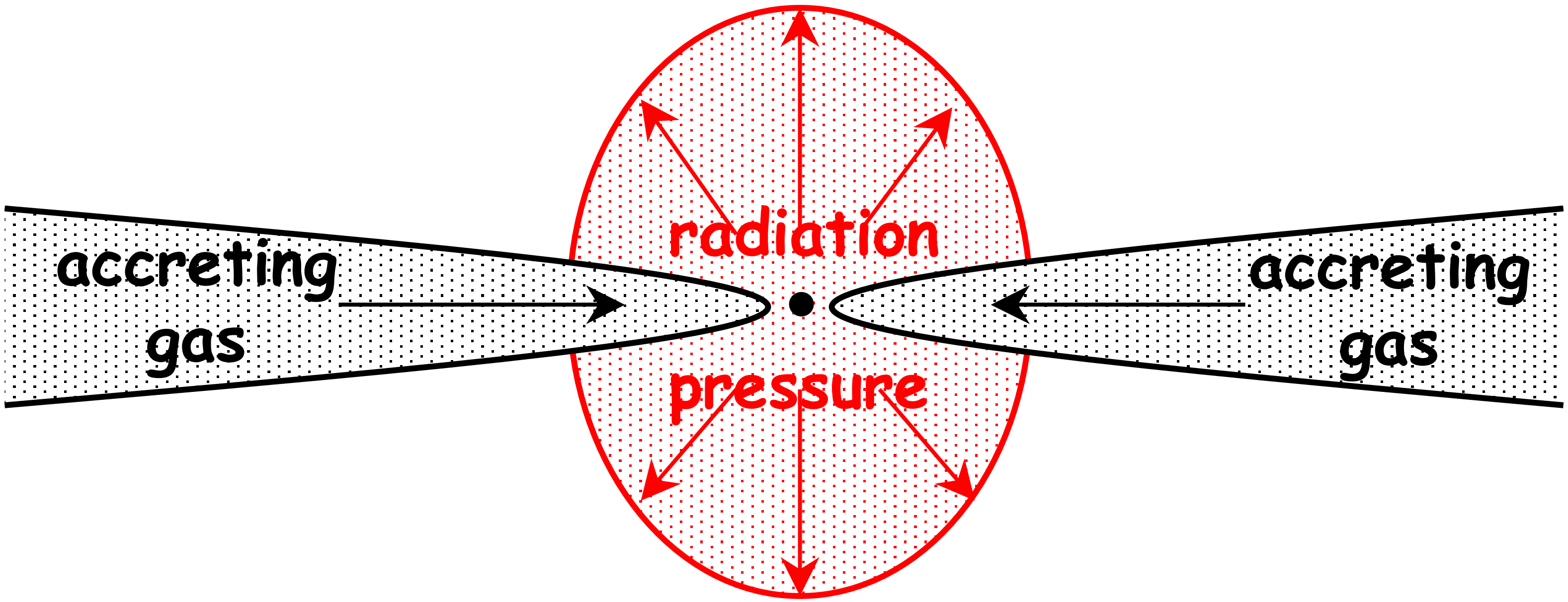
Disk accretion can achieve $L > L_E$

The Eddington luminosity, the classical limit of spherically accreting system, can be exceeded in disk accretion (Abramowicz et al. 1988, Begelman 2002).



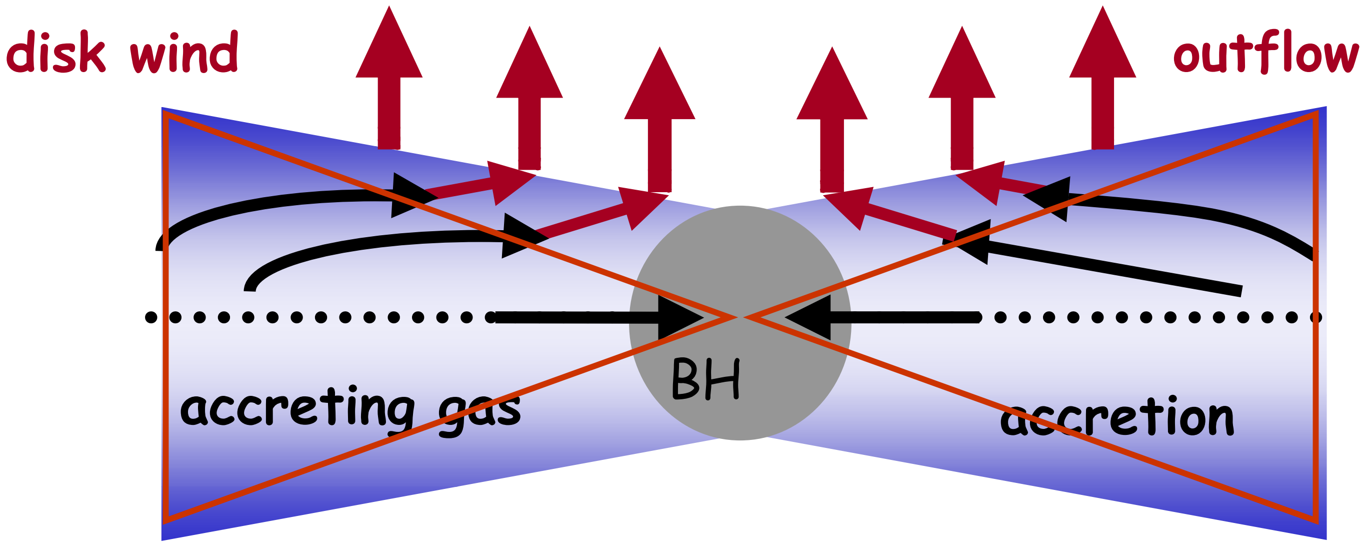
Mass accretion rate can be $\gg L_E/c^2$.

Key process 1. Outflow

(Shakura & Sunyaev 1973; Poutanen et al. 2007)

Significant outflow from disk surface

Radiation pressure-driven outflow inevitably occurs.



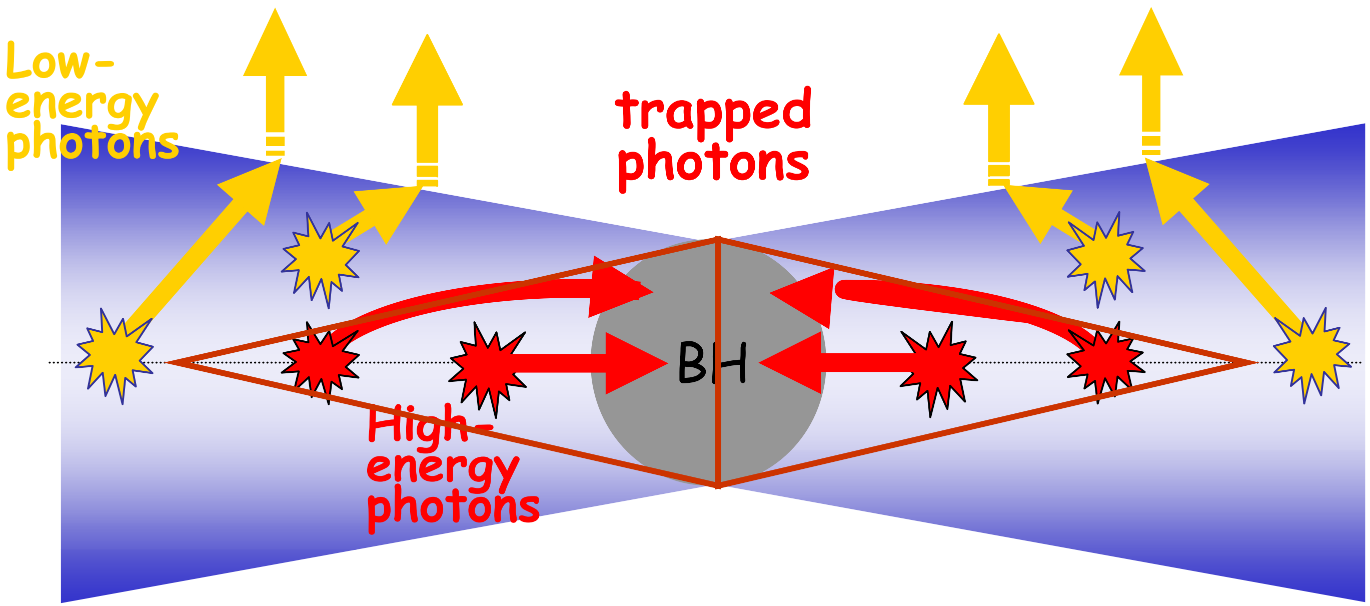
- **Critical radius = spherization radius:** $R_{sp} \sim (\dot{M}c^2/L_E)\, r_s$
- **Inside this radius: flatter** T **profile:** $T \propto r^{-1/2}$

Key process 2. Photon trapping

Begelman (1978), Ohsuga et al. (2002)

Photon trapping within disk

Photons are trapped within luminous accretion flow.



- **Critical radius = trapping radius:** $R_{trap} \sim (\dot{M}c^2/L_E)(H/r)\, r_s$
- **Inside this radius: flatter T profile:** $T \propto r^{-1/2}$

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Why 2D RHD simulations?

One-dimensional models (e.g. standard disk, slim disk, ADAF) are quite useful for understanding the basics of different modes of accretion. However…

- Multi-dimensional gas motions (e.g., circulation, convection, outflow…) are totally neglected.
  → Need 2D/3D simulations

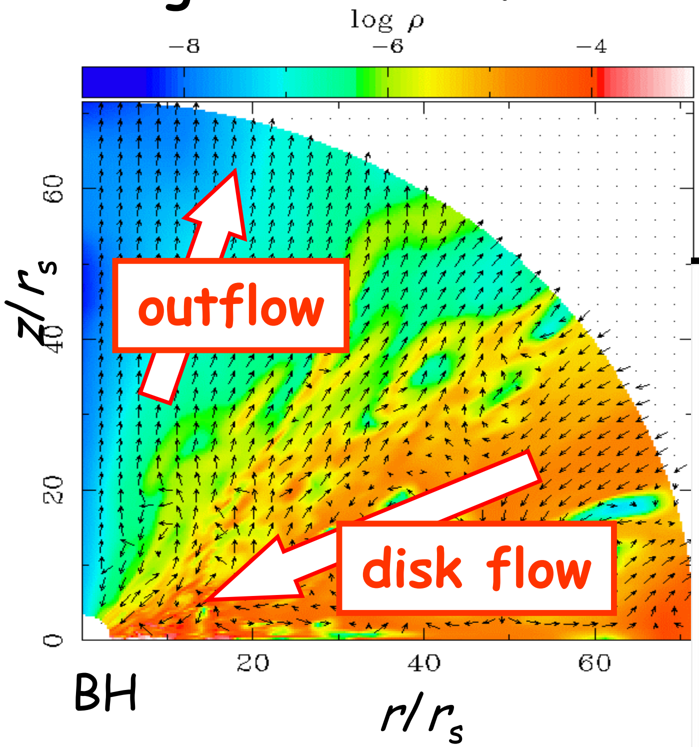
- Strong radiation-matter interactions expected in high luminosity states are not properly treated. → Need radiation hydrodynamics

⇨ $\boxed{\text{We thus need 2D/3D RHD disk simulations.}}$

Overview of supercritical flow

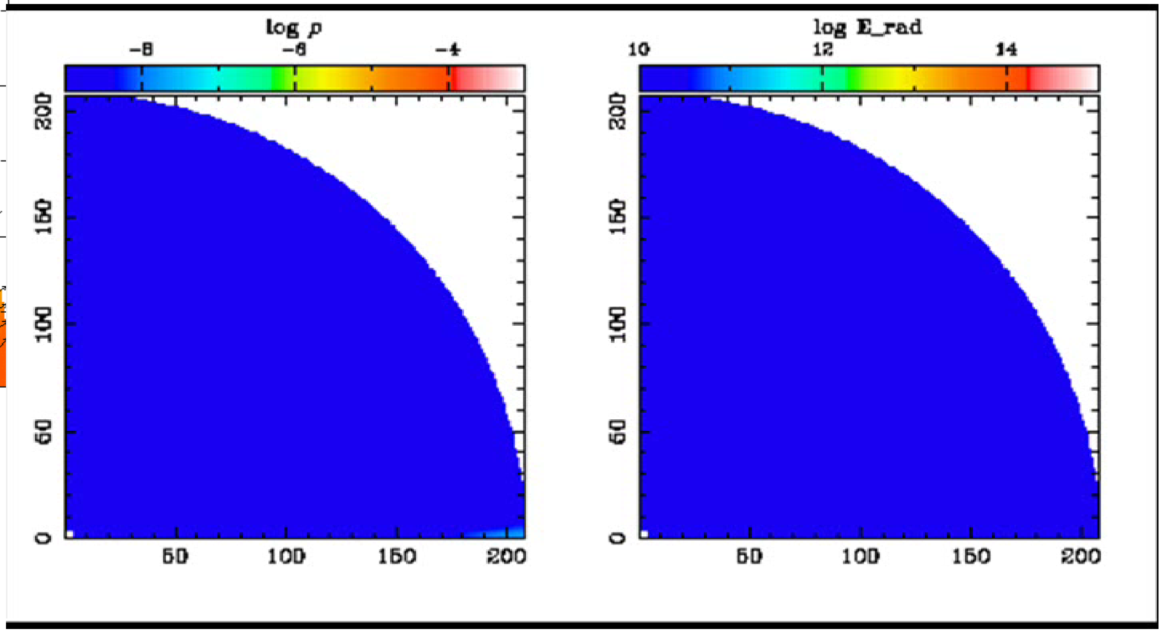
Ohsuga et al. (2005)

- First simulations of supercritical accretion flows in quasi-steady regimes under flux-limited diffusion and α viscosity (α=0.1).



density contours & velocity fields

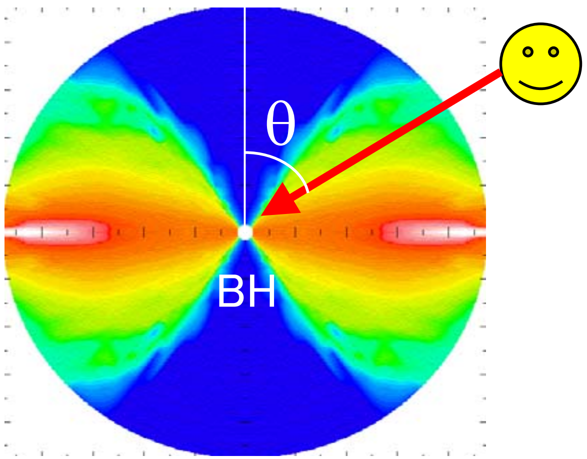
$M = 10\ M_{sun}$ & $\dot{M} \sim 350\ L_E/c^2 \rightarrow L \sim 3\ L_E$



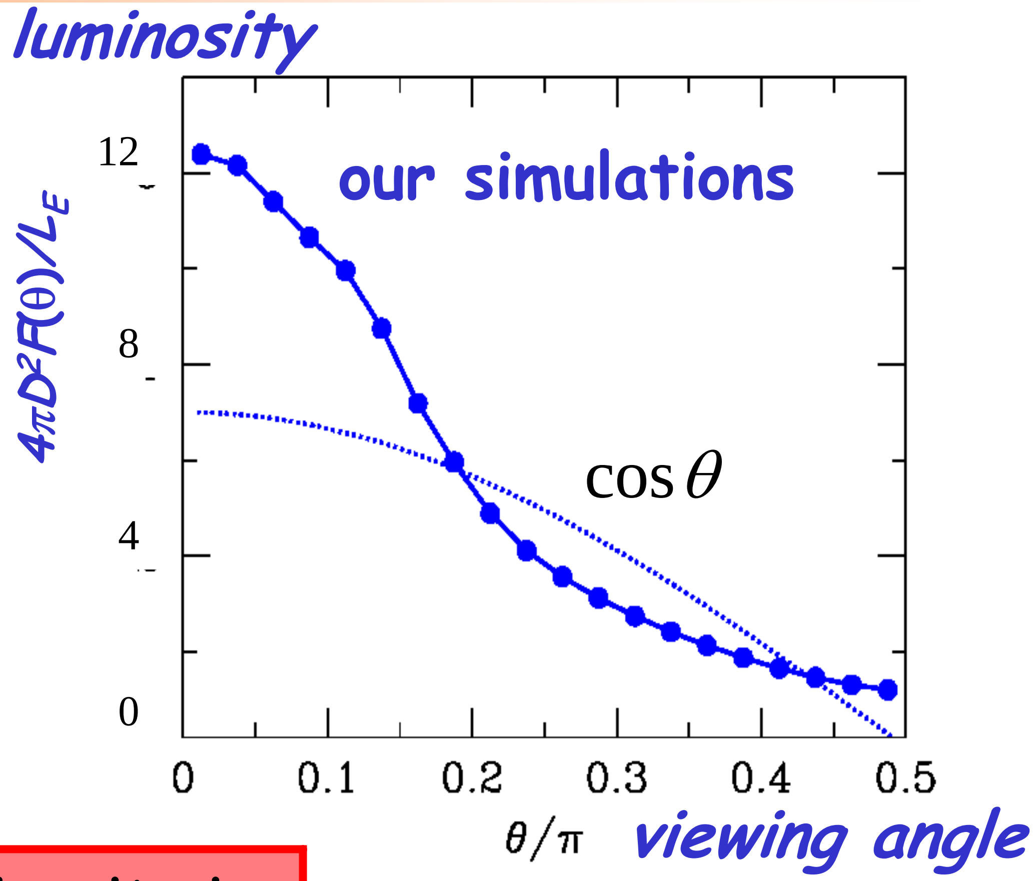
gas density

radiation energy density

Super-Eddington luminosity is realized



Density contours



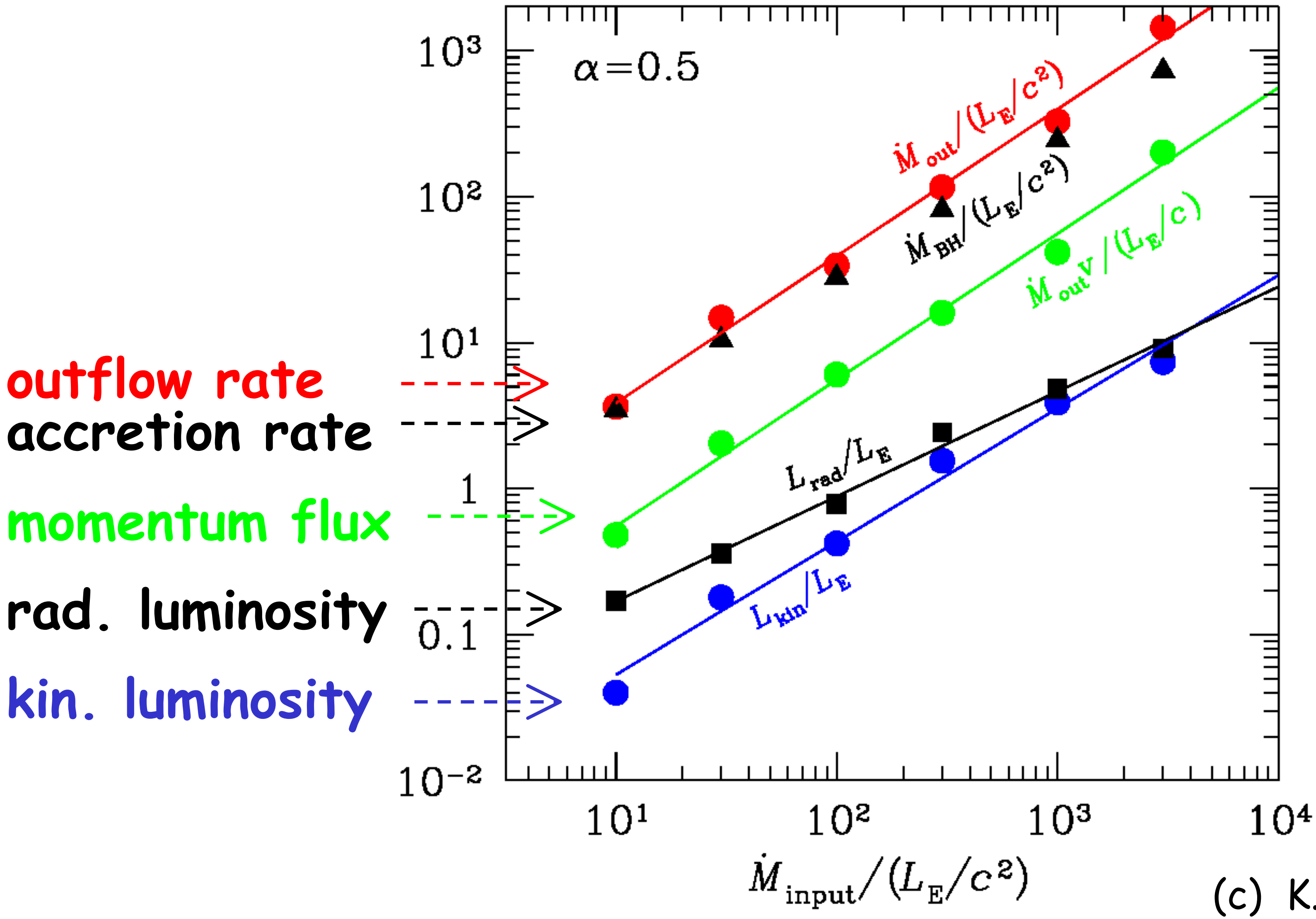
The observed luminosity is sensitive to the viewing-angle; Maximum $L \sim 12\ L_E$!!

⇒ *mild beaming*

(c) K. Ohsuga

No limit on the accretion rate!

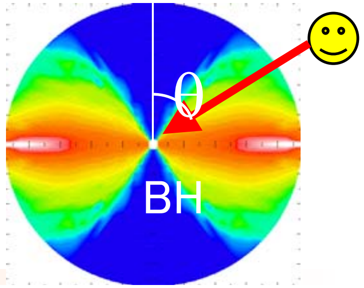
Ohsuga (2007, ApJ 659, 205)

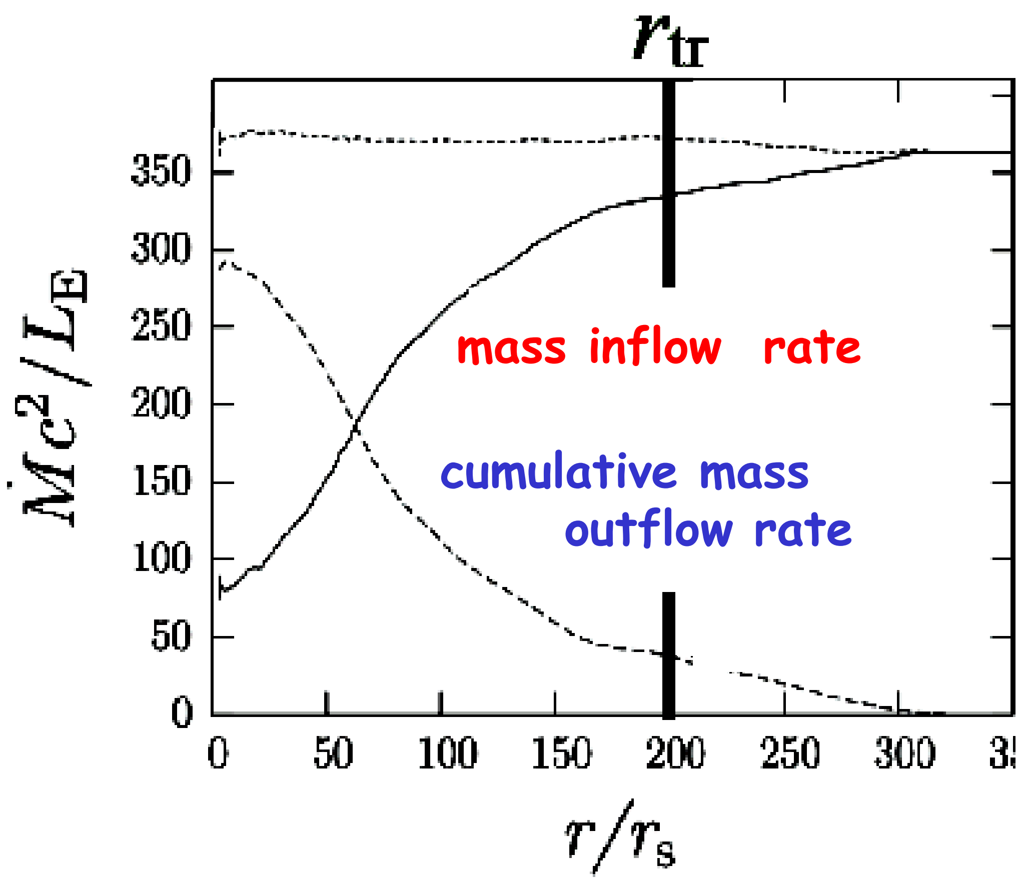


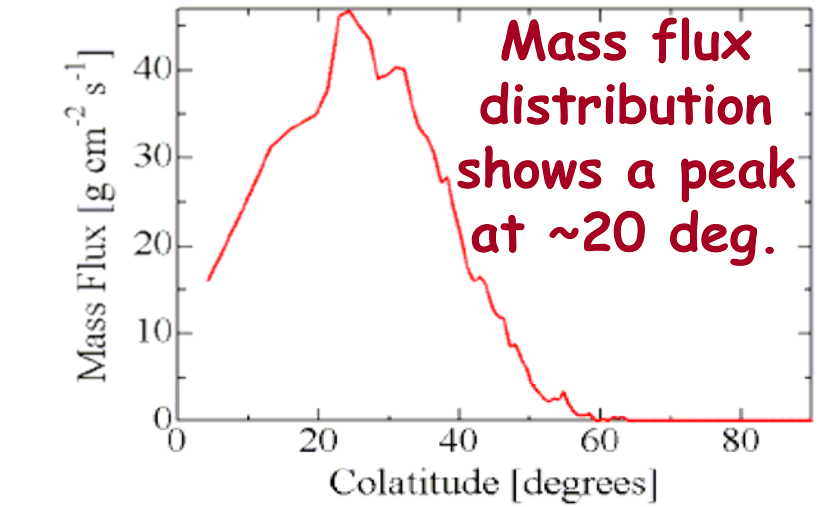
(c) K. Ohsuga

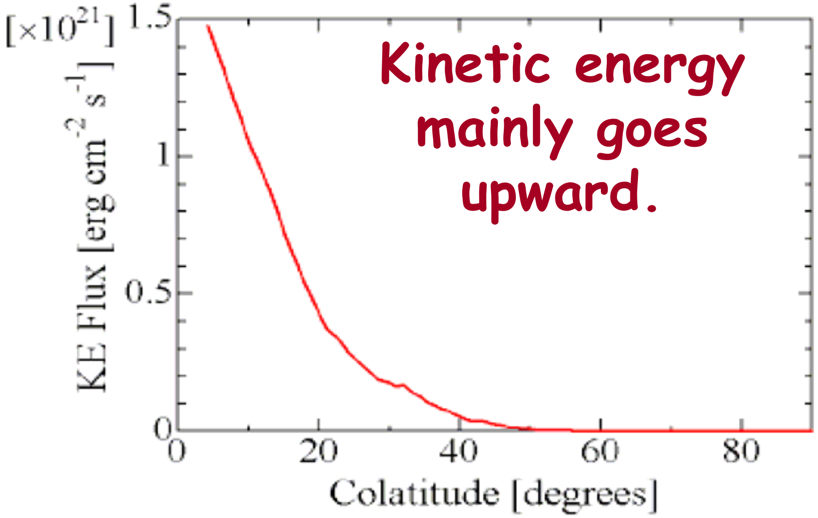
Outflow properties

Takeuchi et al. (2009)





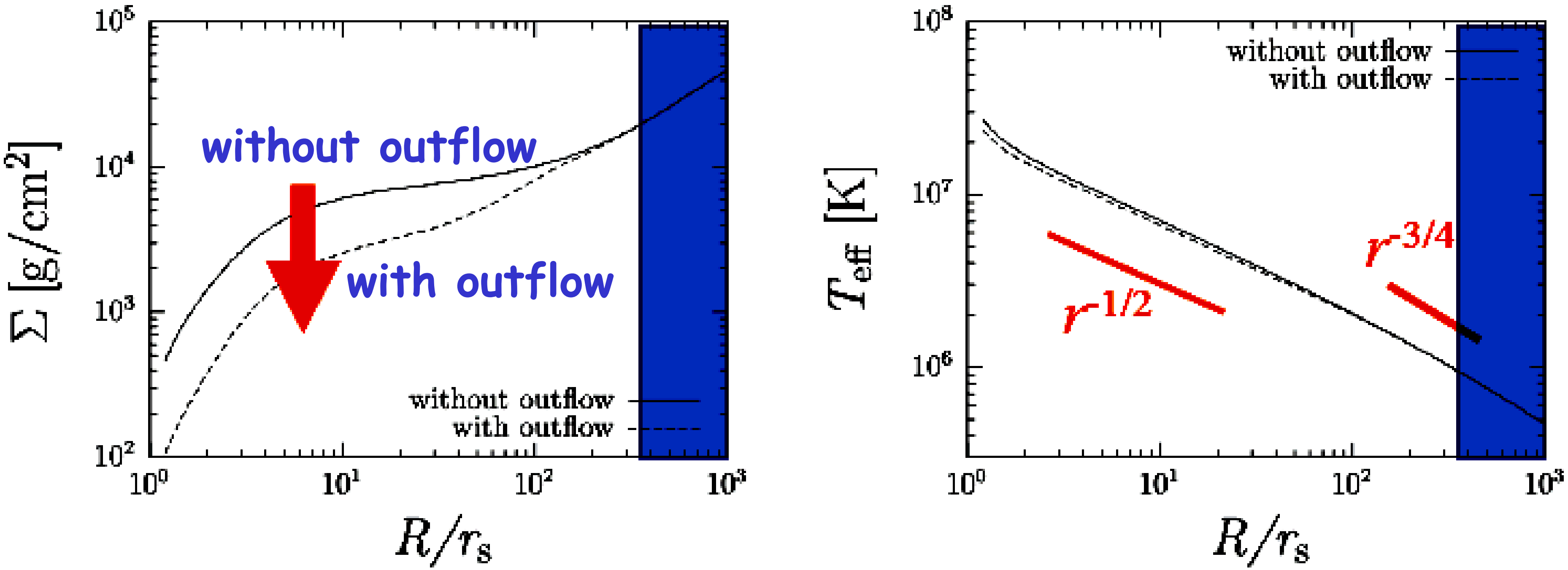




Mass inflow rate decreases inward but is not proportional to *r*.

Slim disks with outflow

(Takeuchi, S.M. & Ohsuga 2009)



If we include outflow…

Σ decreases due to mass loss, but T_{eff} unchanged, because
(1) T_{eff} is determined by photon trapping at small radii;
(2) no outflows appear at large radii.

Compton cooling

(Kawashima, S.M. et al. 2009, PASJ)

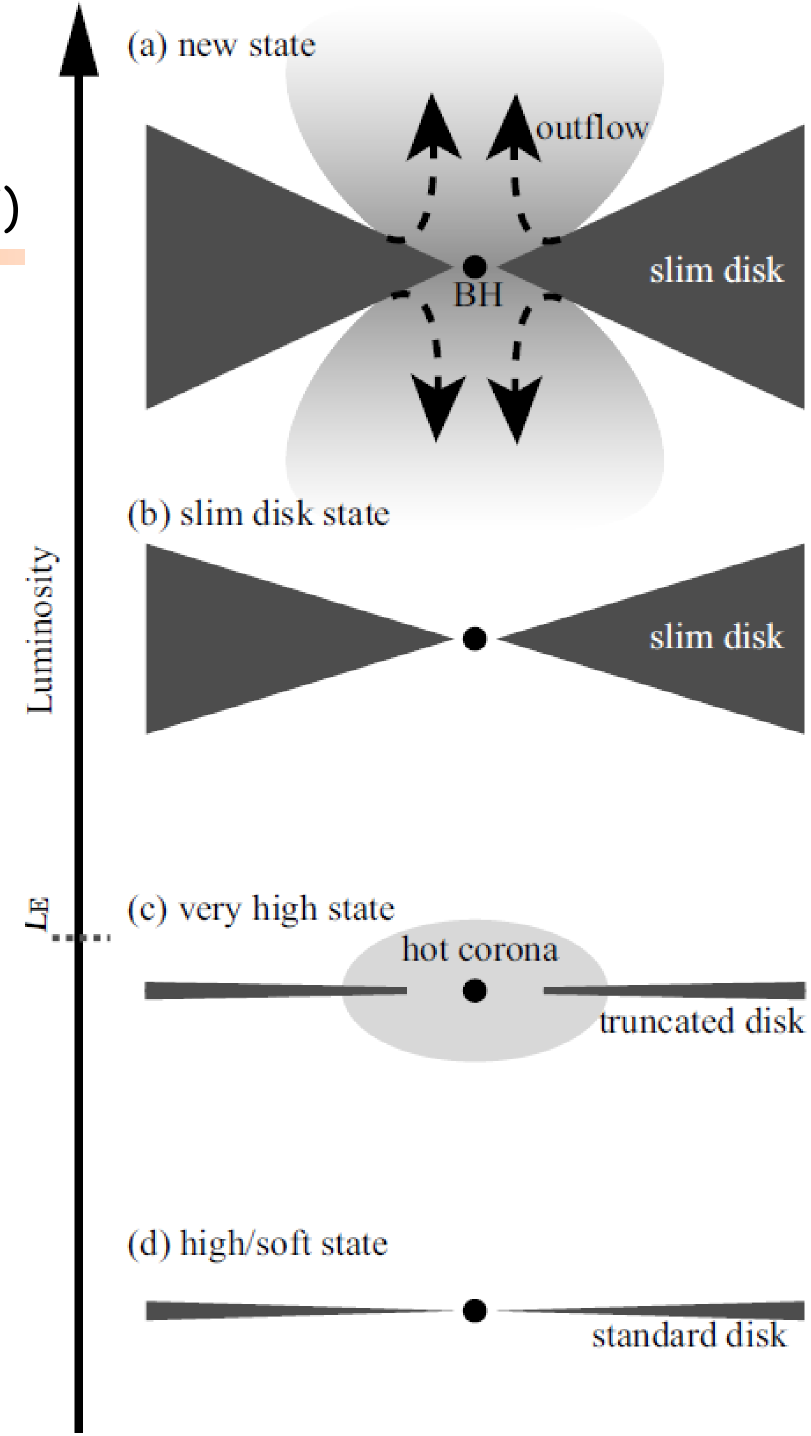
Compton cooling

y-parameter>~1

→ significant cooling of outflow gas

A new supercritical state accompanied with hard power-law emission; PL emission↑ as L↑ (observed in NGC1313-X2).

See poster #9 by Kawashima.



Two important results

- Flatter temperature profile ($T(r) \propto r^{-p}$ with $p<0.75$) :

  Can be proven by the fitting with the extended disk-blackbody (p-free) model (described later).

- Comptonizing corona with low temperature ($kT_e<10$keV) and high optical depth ($\tau>3$) :

  → Mass supply mechanism to corona differ; evaporation of disk material in sub-critical regime while P_{rad} driven outflow in supercritical regime.

  (If Compton $y=[4kT_e/(m_ec^2)](\tau+\tau^2) \sim 1$ as is expected by the energy balance, large $\tau>>1$ leads to low $kT_e<<100$ keV)

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Spectral properties

(e.g. Kato et al. 2008)

Disk spectra = multi-color blackbody radiation

Temp. profiles affect spectra: $F_\nu \propto \int B_\nu(T(r))\, 2\pi r dr$

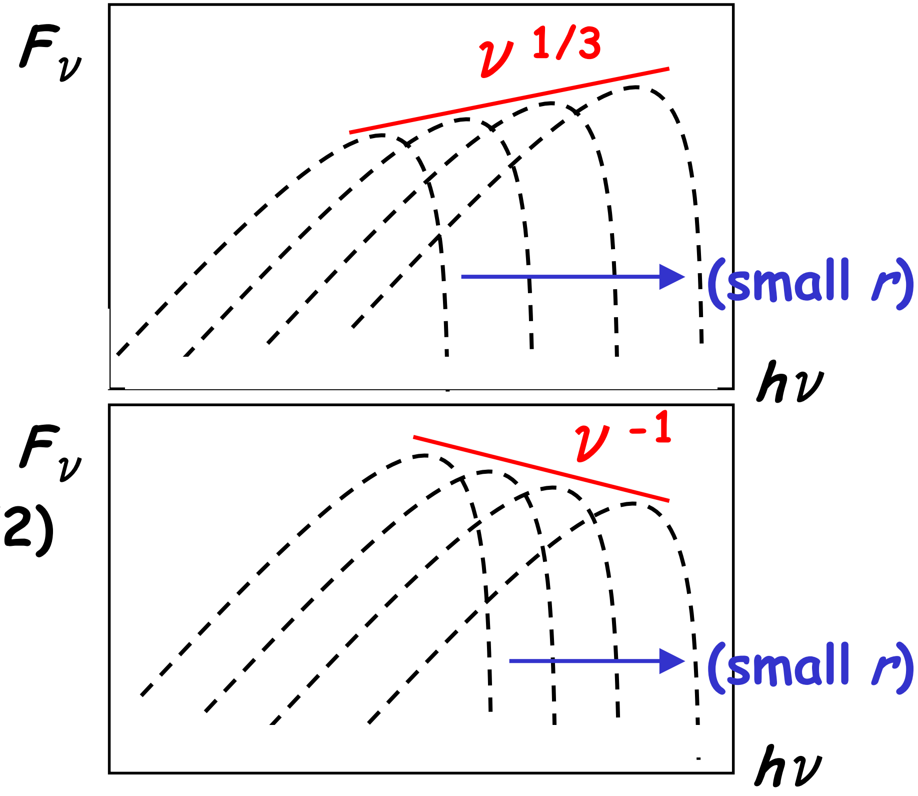
$T \propto r^{-p} \Rightarrow F_\nu \propto \nu^{3-(2/p)}$

- standard disk (p=3/4)

  $\Rightarrow F_\nu \propto \nu^{1/3}$

- supercritical disk (p=1/2)

  $\Rightarrow F_\nu \propto \nu^{-1}$



Extended disk-blackbody model

(Mitsuda et al. 1984; Mineshige et al. 1994)

Fitting with superposition of blackbody (B_ν) spectra:

$$F_\nu = \cos i \int_{r_{in}}^{r_{out}} B_\nu[T(r)] 2\pi r dr; \quad T(r) = T_{\rm in}(r/r_{\rm in})^{-p}$$

Three fitting parameters:

T_{in} = temp.of innermost region (~ max. temp.)

r_{in} = size of the region emitting with $B_\nu(T_{in})$

p = temperature gradient (=0.75 in disk-blackbody model)

Corrections:

Real inner edge is at ~ $\xi\, r_{in}$ with ξ ~0.4

Higher color temp.; $T_c = \kappa\, T_{in}$ with κ ~1.7

⇒ Good fits to the Galactic BHs with p=0.75

Spectral fitting: Extended DBB model

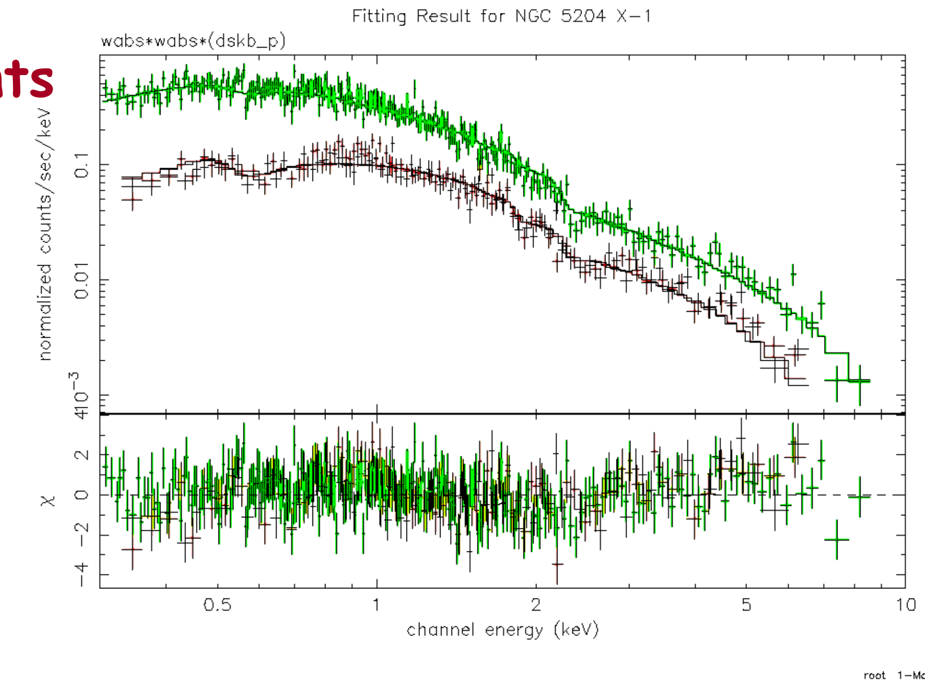
(Vierdayanti et al. 2006)

Model fitting, assuming $T \propto r^{-p}$

We fit the XMM-Newton data of some ULXs

⇒ high T_{in} ~ 2.5 keV and p=0.50±0.03 (no PL comp.)

log conts



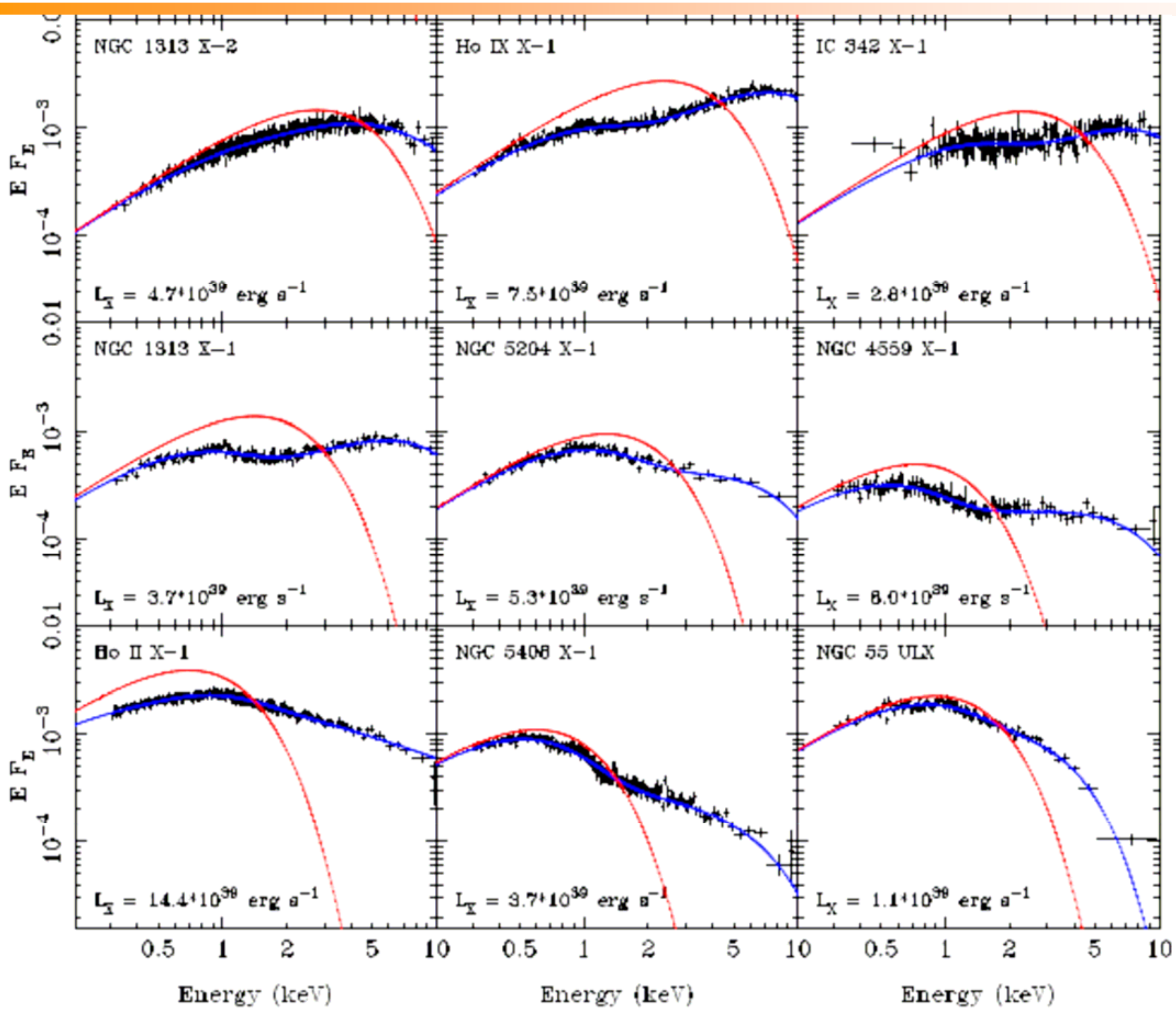
NGC 5204 X-1

log $h\nu$

M_{BH}~ 12 M_{sun} & L/L_E~ 1, supporting supercrit. accretion

Compton-dominated spectra of ULXs

(Gladstone, Roberts, Done 2009)

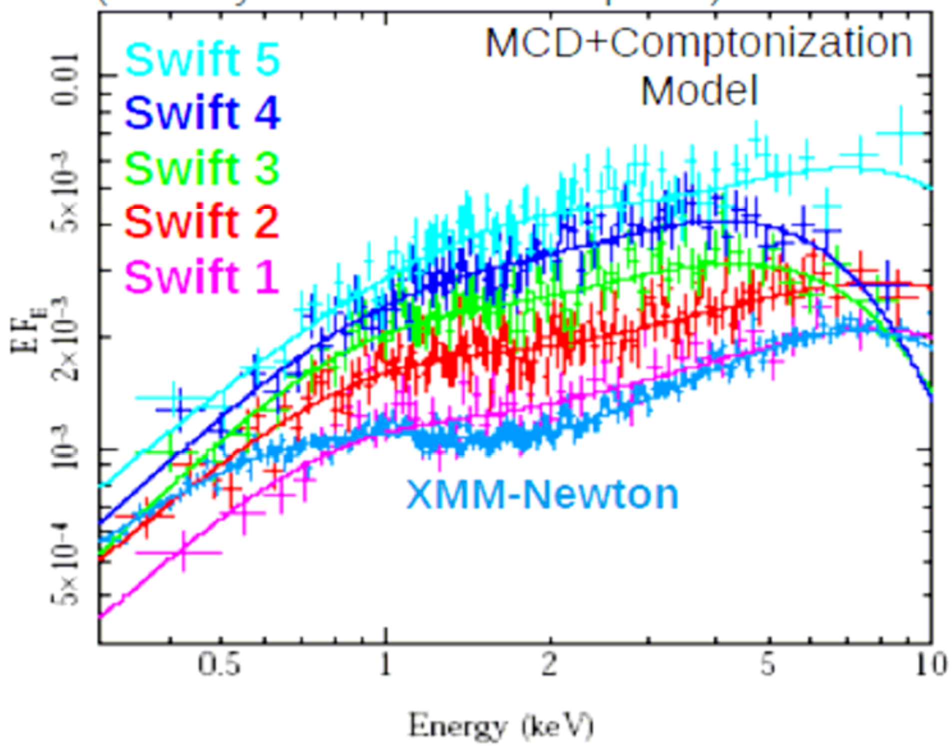


Red lines: original disk emission

Blue lines: scattered emission

Spectral Variability in Holmberg IX X-1

(Vierdayanti et al. 2010 in press)



Significant spectral variability does clearly appear.

Spectral fitting results in the combination of low T_{in} (~ 0.2 keV), and optically-thick (τ > 3), low T_e (< 10 keV) corona.

T_e decreases as the flux increases while T_{in} remains unchanged (except for the highest flux data).

The properties of Comptonization components are similar to that of BHBs at high mass accretion rate.

(Vierdayanti et al. 2010, MNRAS)

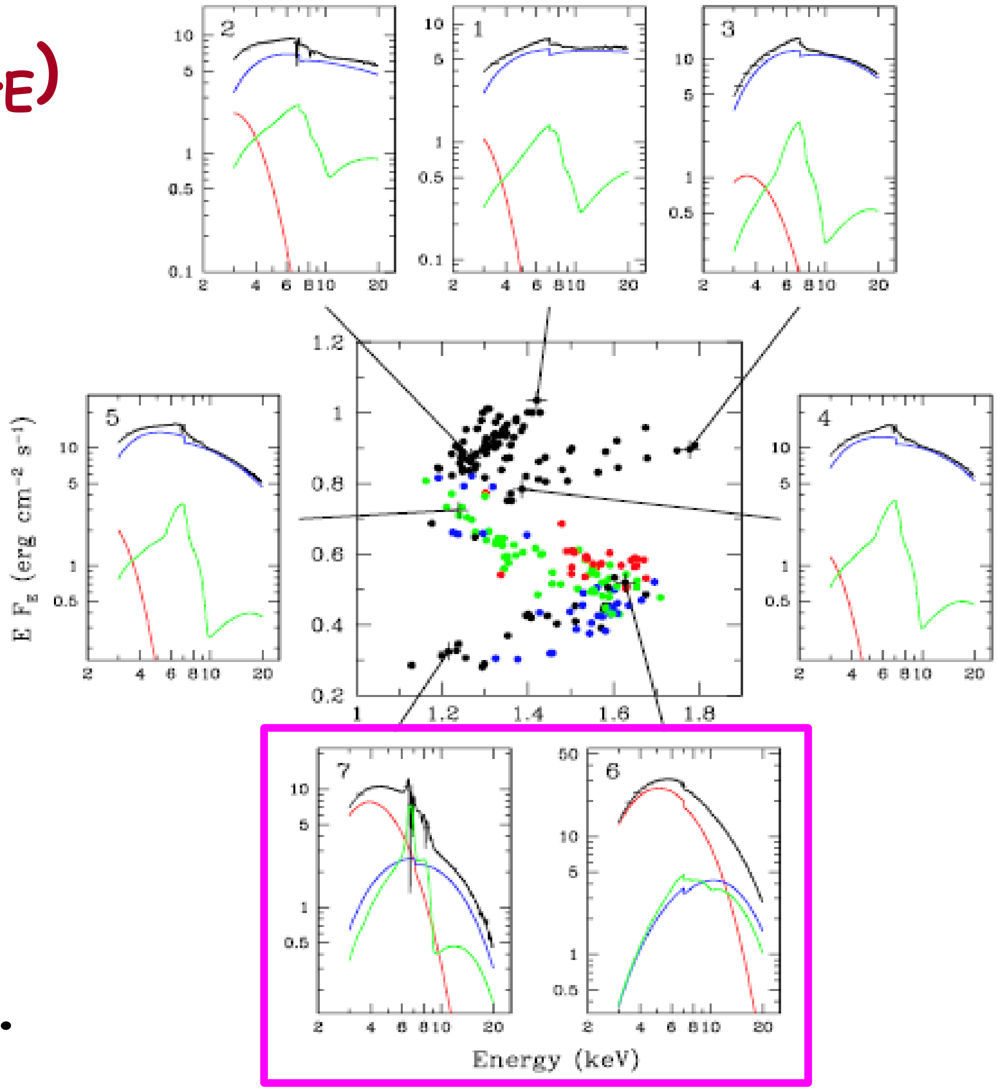
Microquasar, GRS1915+105

(Done et al. 2004)

The brightest (largest L/L_E) BH binary in our Galaxy; BH mass is $14\pm4\ M_{sun}$).

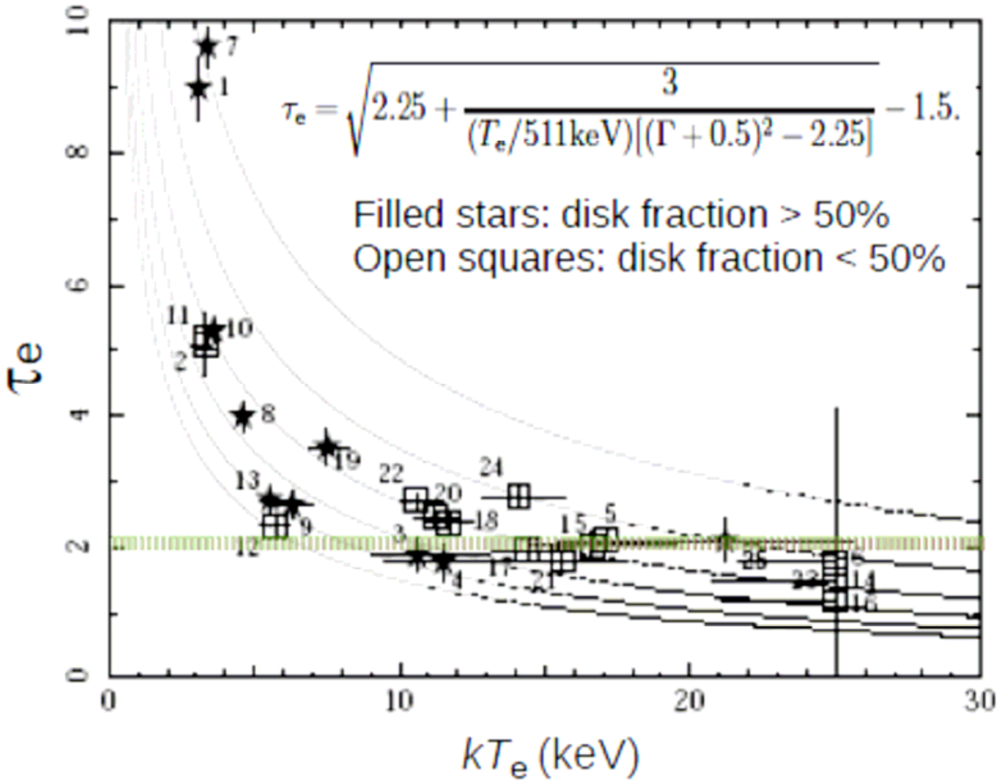
It exhibits exceptionally complex behavior (both of spectra and timing) difficult to understand in a simple way.

We focus on data with relatively soft spectra and with little variability.



Low Temperature and Optically Thick Corona

Compton dominated spectra in normal BHBs with low luminosity show $T_e > 100$ keV, $\tau_e \sim 1$.



In GRS 1915+105, low T_e (< 20 keV) and Γ (~ 2 – 4) results in τ_e mostly > 2.

BHBs at high luminosity state also prefer low temperature (and optically thick) corona (e.g. XTE J1550+564 (Done & Kubota 2006)).

Low electron temperature and high electron scattering optical depth are commonly found in high luminosity systems.

(Vierdayanti et al. 2010, PASJ)

Tracks in L-T diagram

(Vierdayanti, Ueda, SM, 2010)

2-3 groups of data

Lower branch:

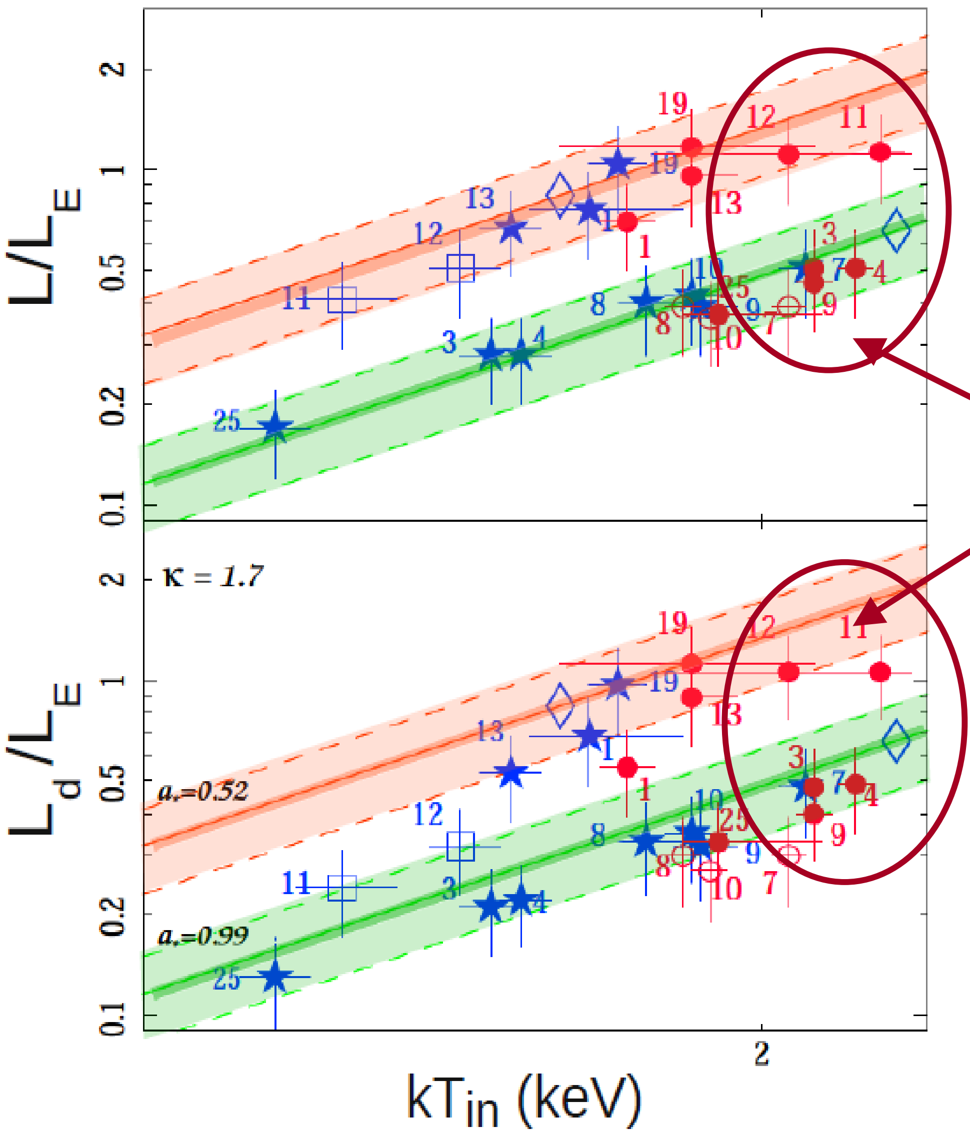
standard disk with $L_d \propto T^4$ (extending down to $\ll L_E$)

No $L_d \propto T^2$ branch

(because of high spin?)

Upper branch:

obscuration?



P~0.6

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Why global RMHD simulations?

- Global RHD simulations exhibited unique features of supercritical accretion. However…

  Disk viscosity was treated by the phenomenological α model. Its validity needs to be examined.

- Local RMHD simulations were performed and they show well-resolved vertical structure. However…

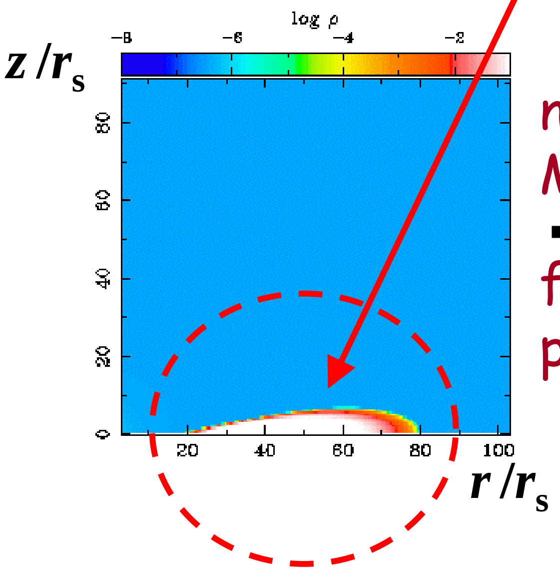
  Global magnetic field coupling, which seems to be essential for creating jets, was ignored.

⇨ We thus need global RMHD simulations.

Global 2D RMHD simulations

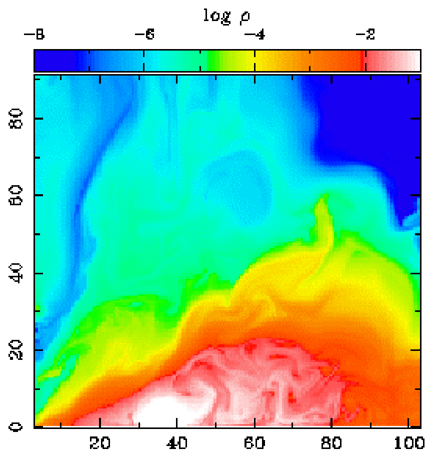
Ohsuga, SM, et al. (2009, PASJ 61, L7)

- **Radiation and MHD processes are both considered.**
- **Start with a torus threaded weak poloidal fields:**



non-radiative MHD simulation

for 4.5 rotation periods



turn on

radiation terms

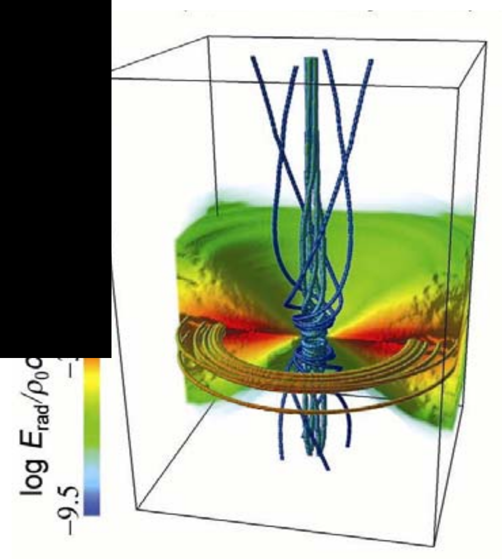
- **Three different regimes (ρ_0=density normalization)**

⇨ **Model A ($\rho_0=10^0$ g/cm^3) : supercritical (very luminous) state**

Model B ($\rho_0=10^{-4}$ g/cm^3) : standard-disk state

Model C ($\rho_0=10^{-8}$ g/cm^3) : radiatively inefficient flow state

Radiation-MHD simulation: model A

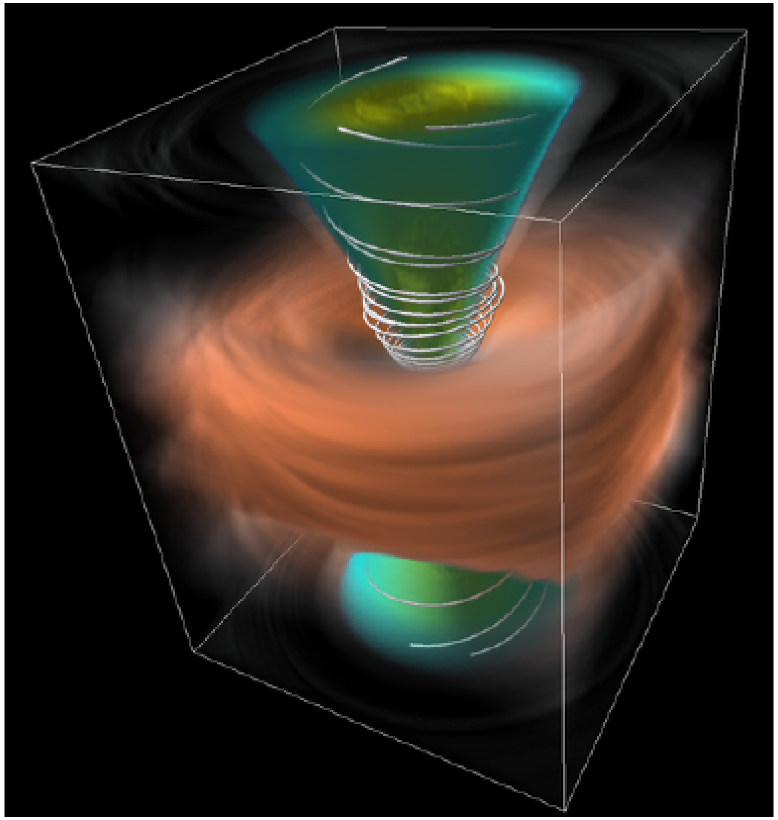


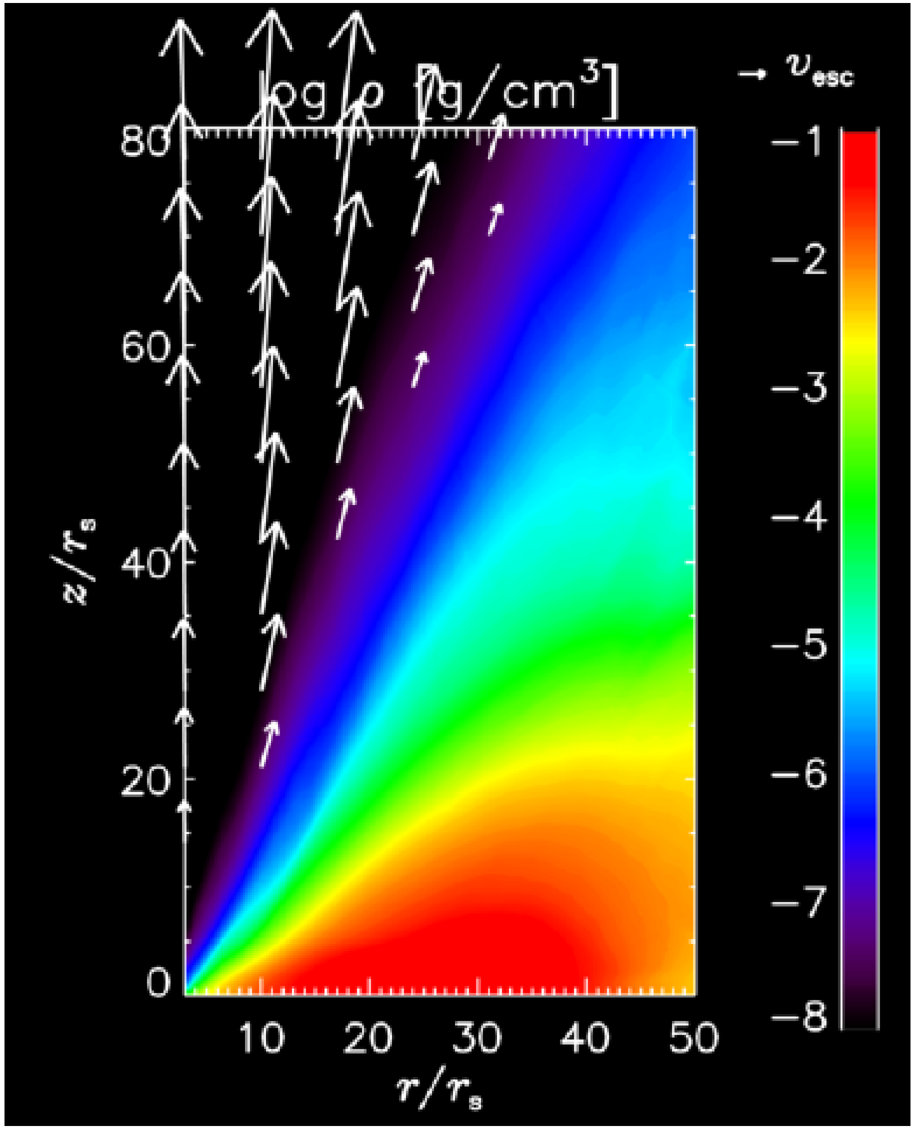
New type jet? - RMHD jet

(Takeuchi, SM, Ohsuga, PASJ, submitted)

A "magnetic tower jet" is found in the RMHD simulation.

Right: density contours & velocity vectors.





Summary

- Supercritical accretion is feasible and is expected to exhibit several distinct observable features, such as super-Eddington luminosity, mild beaming, significant high-speed outflow, hard power-law radiation, etc.

Apparent luminosity can be >~ 10 L_E !!

- Two theoretical expectations, flatter temperature profiles and low-temperature, optically thick Comptonizing corona, seem to be observed in some ULXs and microquasars (e.g. GRS1915+105).

- Global RMHD simulations are in progress. A new type of jet (RMHD jet) is produced at high luminosities.