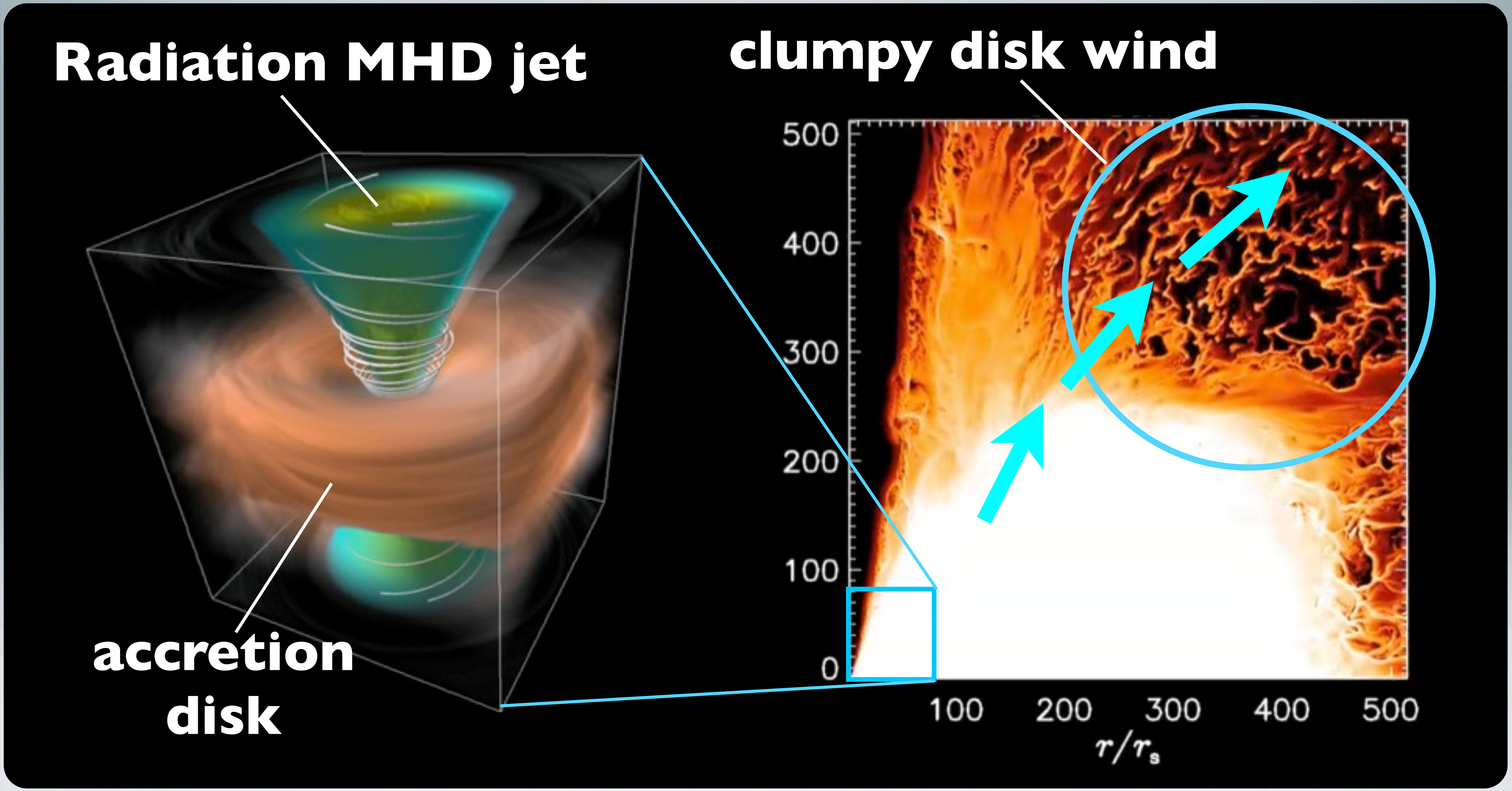
Radiation Magnetohydrodynamics of Black Hole Accretion Flows and Outflows

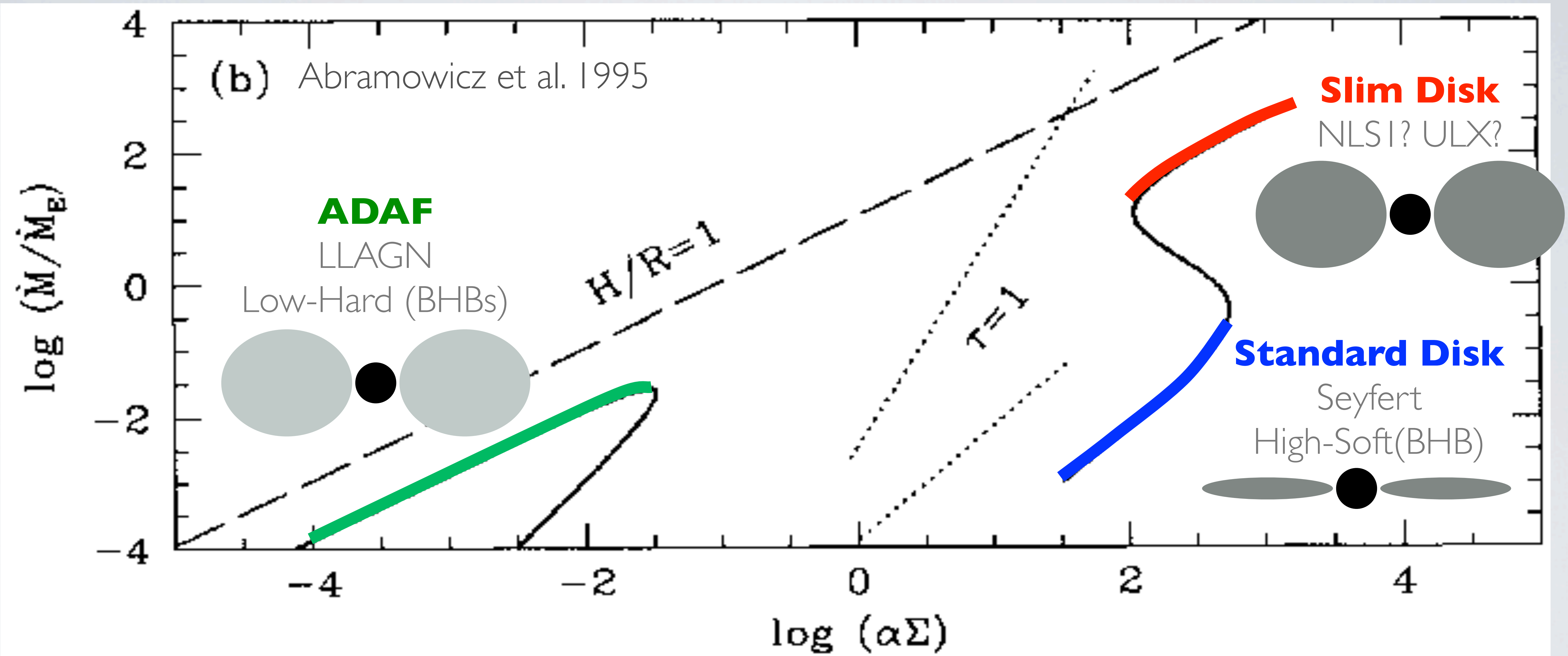


Ken OHSUGA (NAOJ, Japan)

S. Mineshige, S. Takeuchi, T. Kawashima, H. Takahashi, M. Nomura

Three States of Accretion Flows and Outflows

THREE DISK MODELS



	AFAF	Standard	Slim
Magnetic effects	YES	YES	YES
Radiative Cooling	NO	YES	YES
Radiation Force	NO	NO	YES

RADIATION-MHD SIM. (WITHOUT ALPHA-VISCOSITY)

$$\frac{\partial \rho}{\partial t} + \boldsymbol{\nabla} \cdot (\rho \boldsymbol{v}) = 0$$

$$\frac{\partial (\rho \boldsymbol{v})}{\partial t} + \boldsymbol{\nabla} \cdot \left(\rho \boldsymbol{v}\boldsymbol{v} - \boxed{\frac{\boldsymbol{B}\boldsymbol{B}}{4\pi}} \right) = -\boldsymbol{\nabla} \left(p + \boxed{\frac{|\boldsymbol{B}|^2}{8\pi}} \right) + \boxed{\frac{\chi}{c} \boldsymbol{F}_0} - \rho \boldsymbol{\nabla} \psi$$

$$\frac{\partial e}{\partial t} + \boldsymbol{\nabla} \cdot (e \boldsymbol{v}) = -p \boldsymbol{\nabla} \cdot \boldsymbol{v} + \boxed{\frac{4\pi}{c^2} \eta J^2} - \boxed{4\pi \kappa B + c\kappa E_0}$$

$$\boxed{\frac{\partial E_0}{\partial t} + \boldsymbol{\nabla} \cdot (E_0 \boldsymbol{v}) = -\boldsymbol{\nabla} \cdot \boldsymbol{F}_0 - \boldsymbol{\nabla} \boldsymbol{v} : \mathbf{P}_0 + 4\pi \kappa B - c\kappa E_0}$$

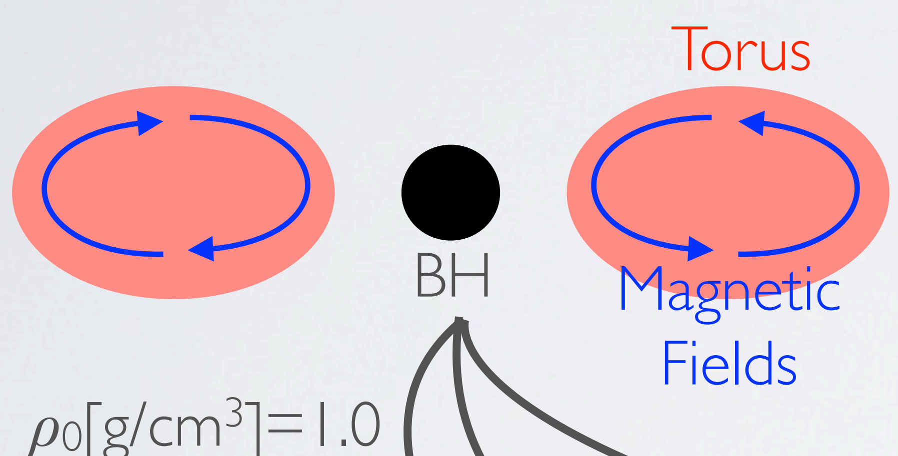
$$\boxed{\frac{\partial \boldsymbol{B}}{\partial t} = \boldsymbol{\nabla} \times \left(\boldsymbol{v} \times \boldsymbol{B} - \frac{4\pi}{c} \eta \boldsymbol{J} \right) \qquad \boldsymbol{J} = \frac{4\pi}{c} \boldsymbol{\nabla} \times \boldsymbol{B}}$$

RHD terms

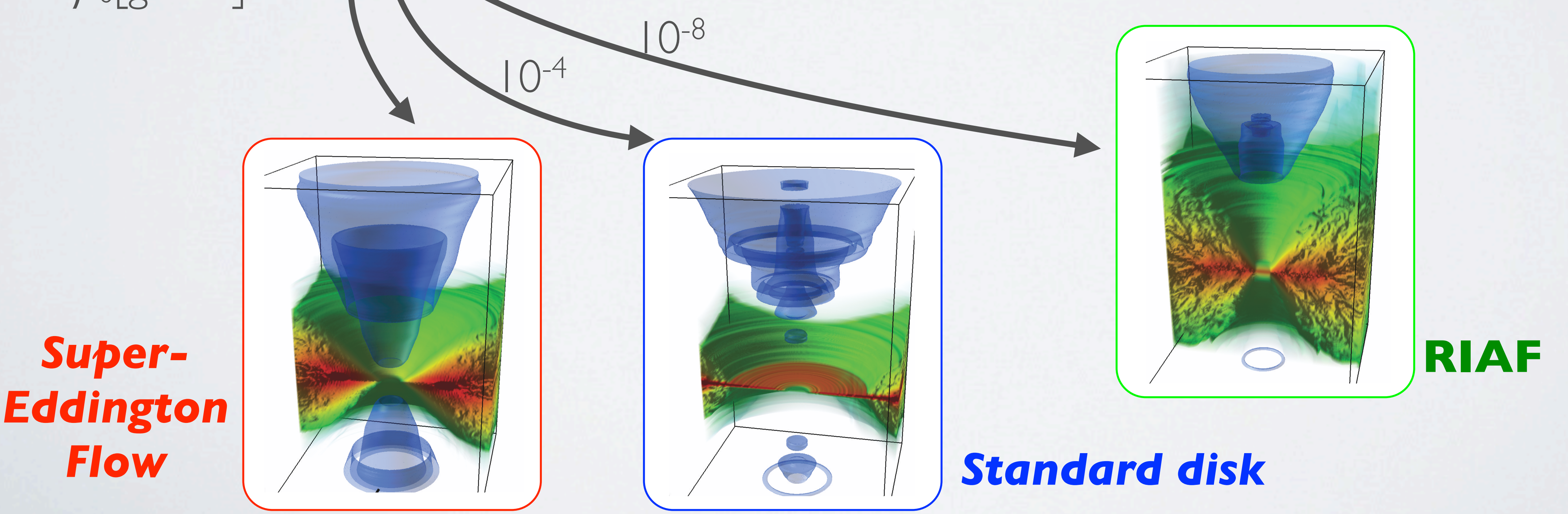
MHD terms

NUMERICAL METHOD

- Cylindrical coordinate (r, φ, z); r=2-100Rs, z=0-100Rs
- We employ Flux-limited diffusion (FLD) for radiation fields.
- Axisymmetry & Mid-plane Symmetry
- Initial Conditions & density parameter

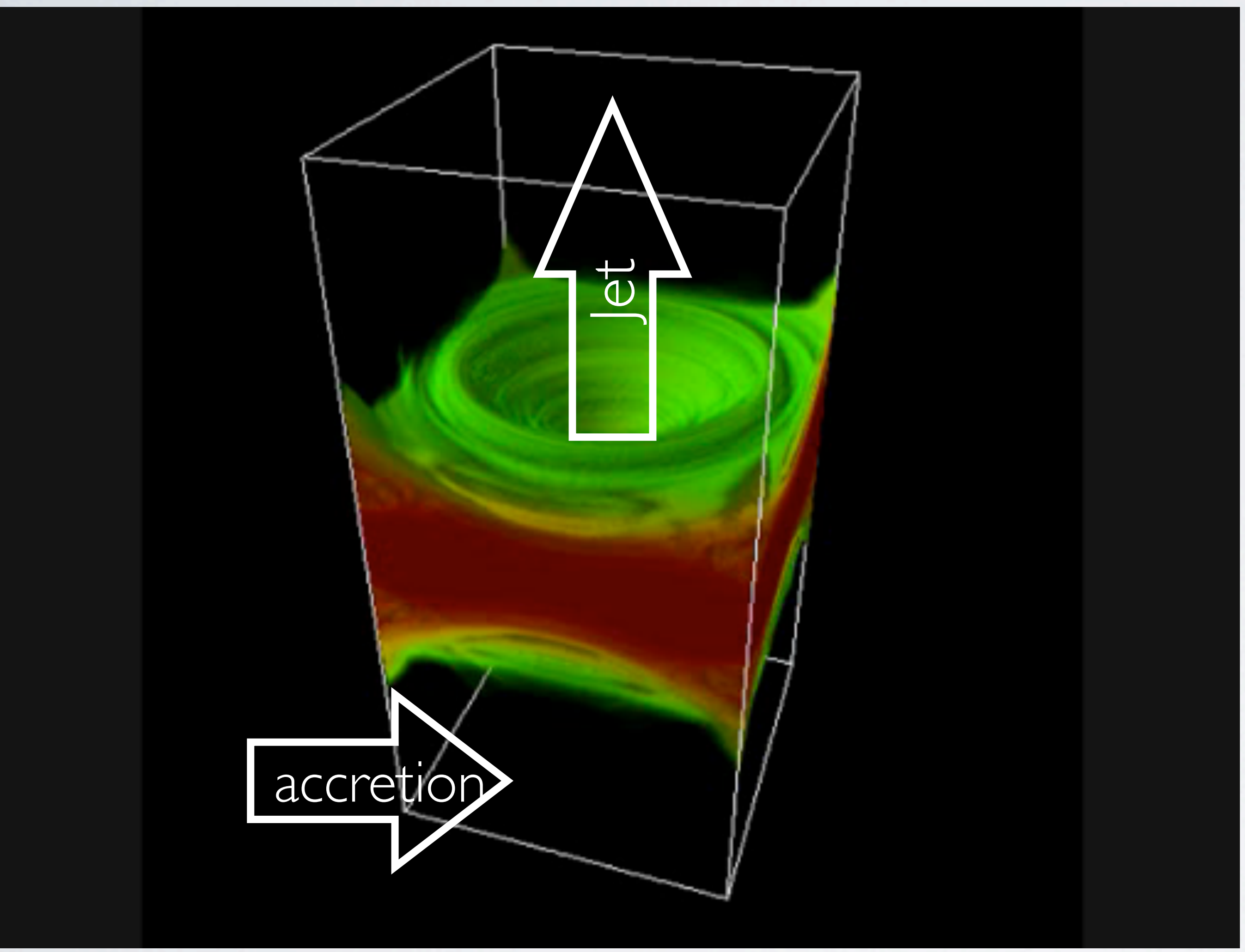


-Rotation torus (plasma-beta=100, closed poloidal magnetic fields; B_φ=0)
-Non-rotating corona ($\boldsymbol{B}$=0)
-We set the density parameter, ρ_0 (density at the center of the torus).

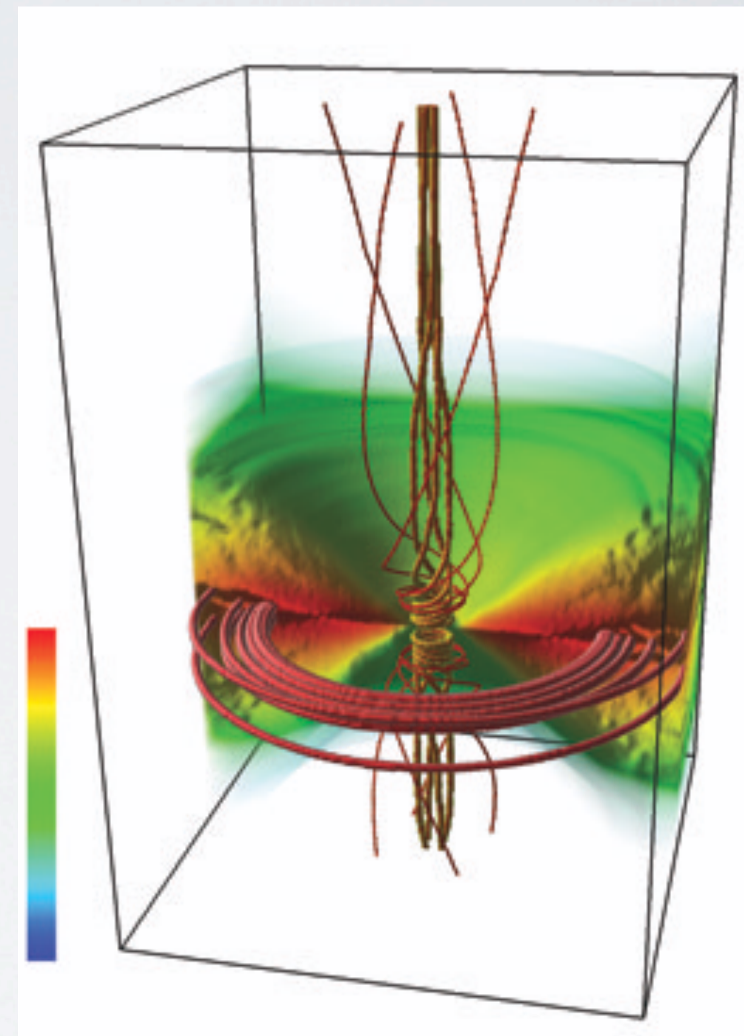


SUPER-EDDINGTON (SLIM) DISK

ρ/ρ_0, [ρ_0=1.0 g cm^{-3}]



Radiation energy & Magnetic field lines



M_{BH}=10Msun

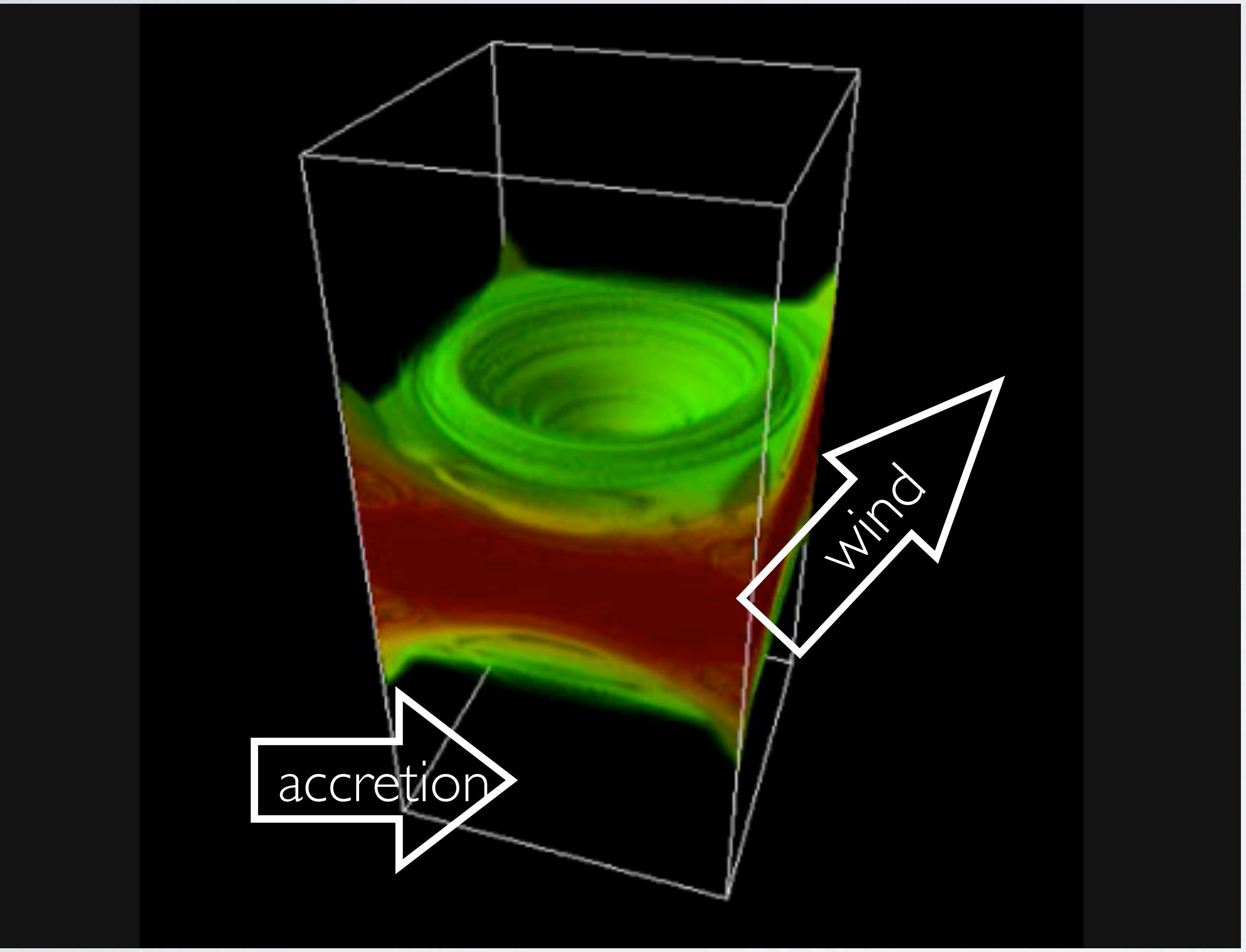
$L_{bol} \gtrsim L_{edd}$, Mdot~60 L_{edd}/c^2

Radiation-pressure supported disk + radiatively-driven jet

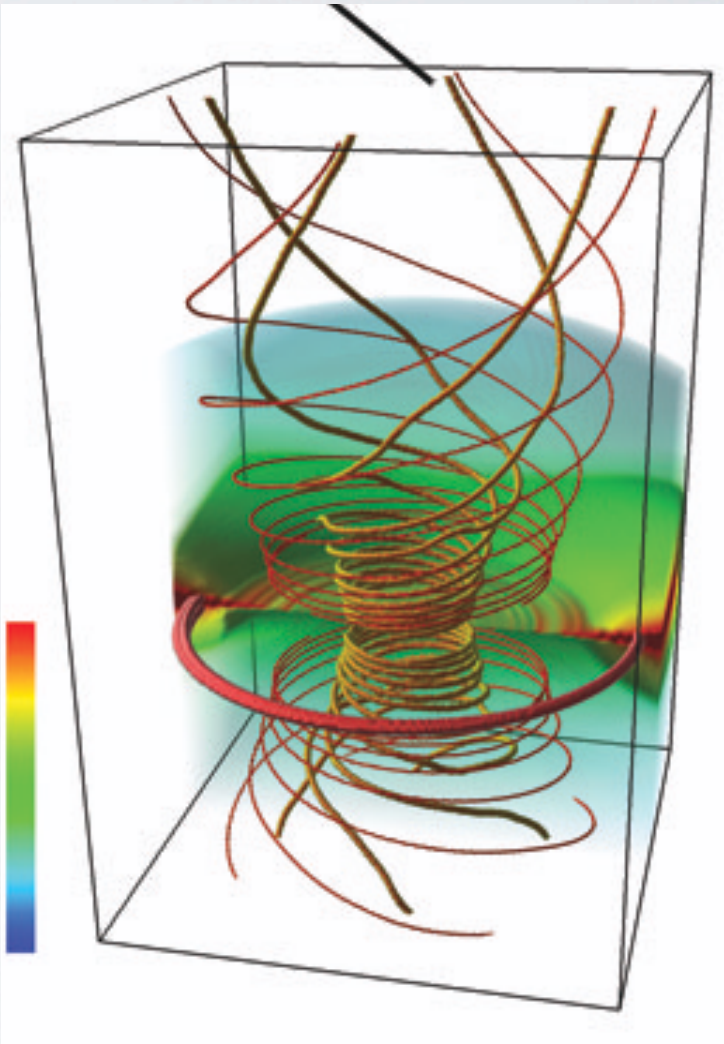
Download; http://th.nao.ac.jp/MEMBER/ohsuga/Ken_Ohsugas_Home_Page/Research.html

STANDARD DISK

ρ/ρ_0, [ρ_0=10^{-4} g cm^{-3}]



Radiation energy & Magnetic field lines

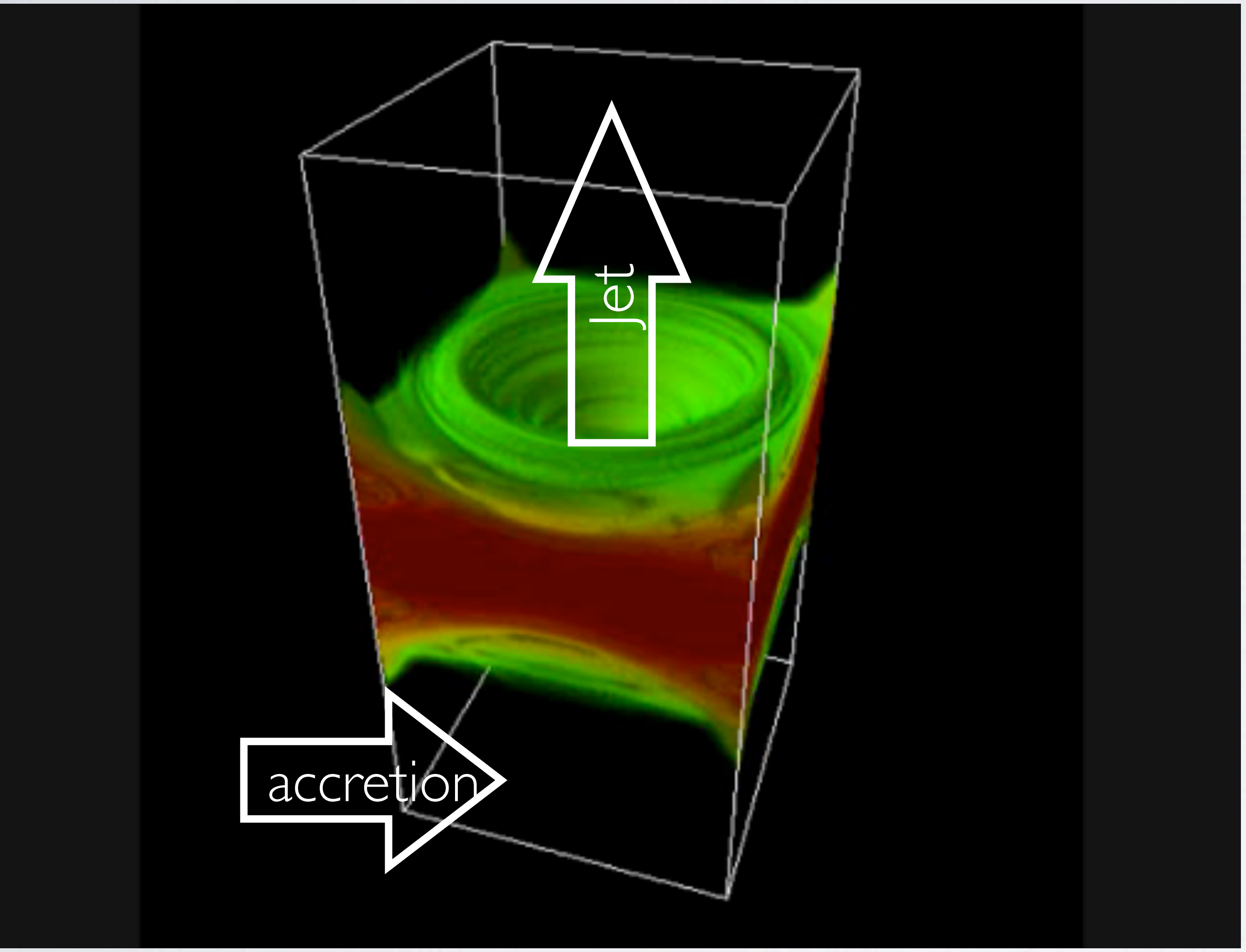


$L_{bol} \sim 10^{-4} L_{edd}$, $Mdot \sim 10^{-3} L_{edd}/c^2$

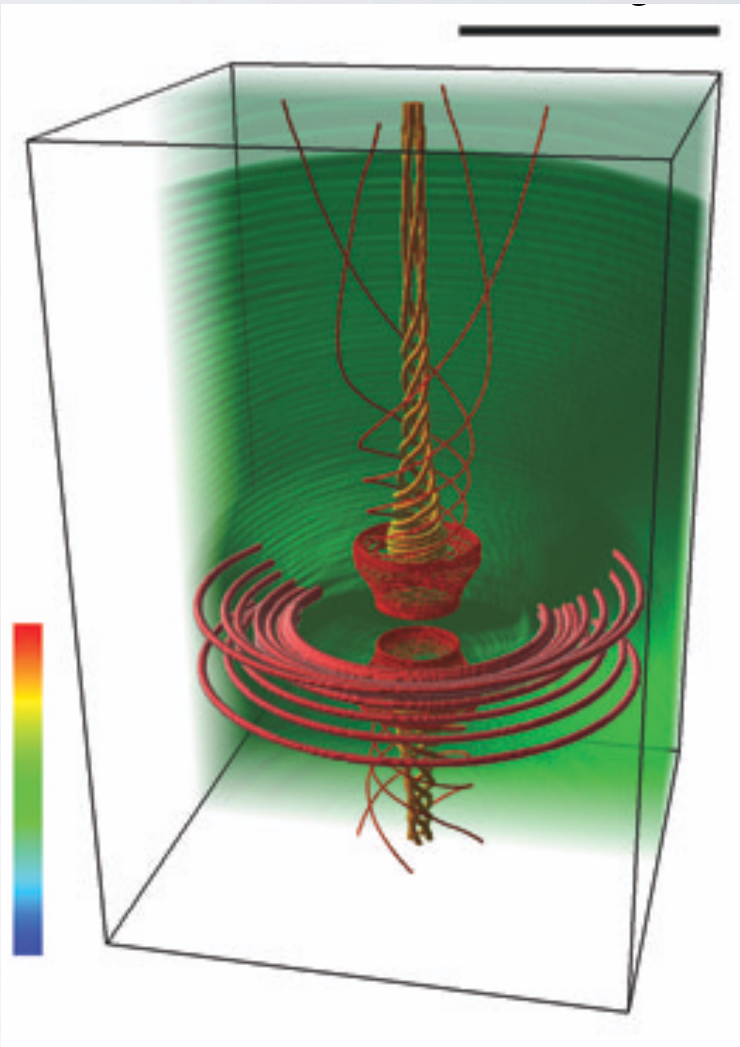
Cold, thin disk + Magnetic pressure driven wind (not strong)

RIAF(ADAF)

ρ/ρ_0, [ρ_0=10^{-8} g cm^{-3}]

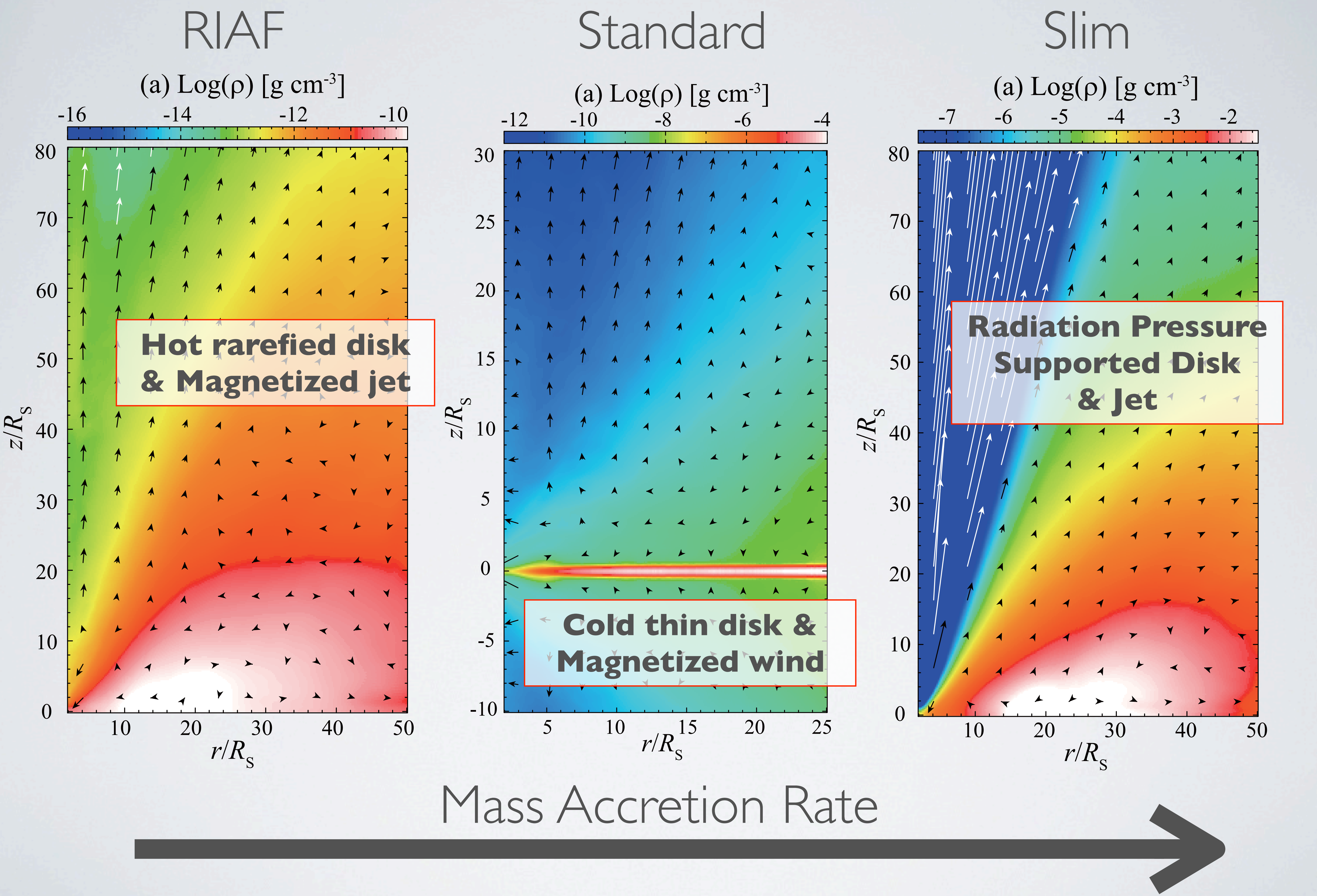


Radiation energy & Magnetic field lines



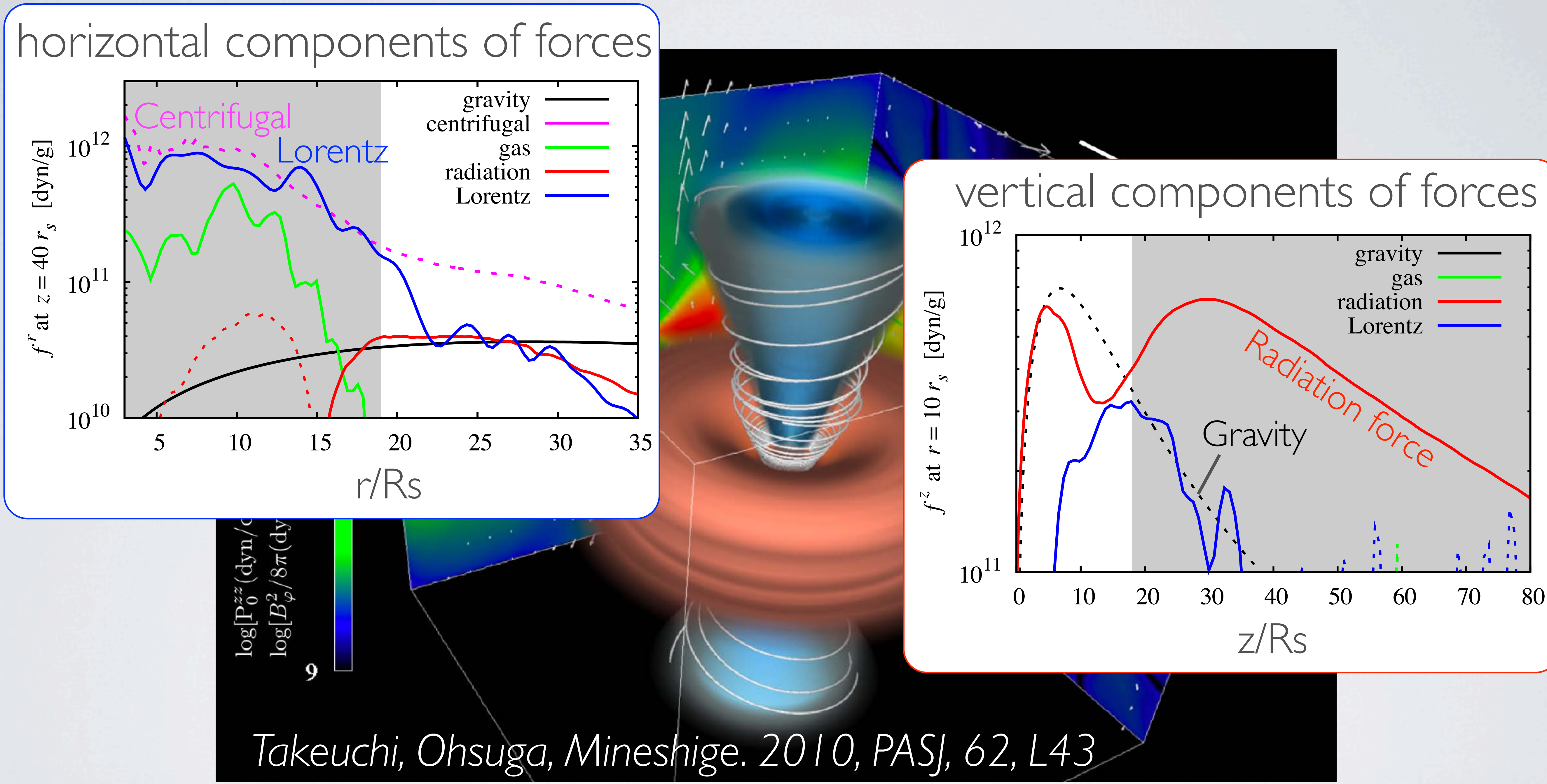
$L \sim 10^{-12} L_{edd}$, $Mdot \sim 10^{-5} L_{edd}/c^2$

Optically thin, hot disk & Magnetic jet


RIAF
Standard
Slim
(a) Log(ρ) [g cm⁻³]
Hot rarefied disk & Magnetized jet
Cold thin disk & Magnetized wind
Radiation Pressure Supported Disk & Jet
z/R_S
r/R_S
Mass Accretion Rate

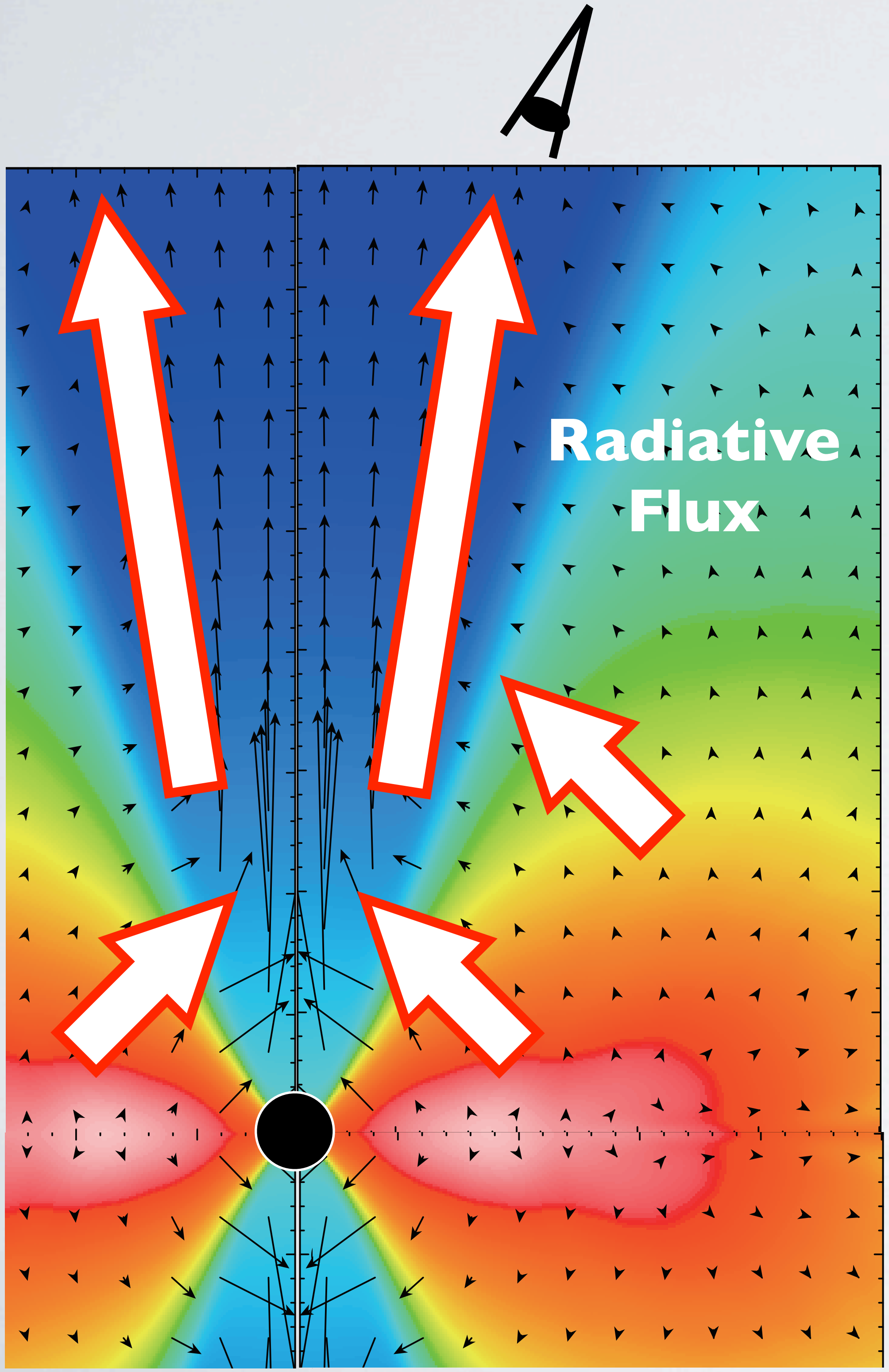
Super-Eddington Flows

RADIATION-MHD JETS



Our RMHD simulations reveal a new type of jet;
Radiatively-accelerated and magnetically collimated jet

OBSERVED LUMINOSITY



- The radiative flux is mildly collimated since the disk is optically and geometrically thick.

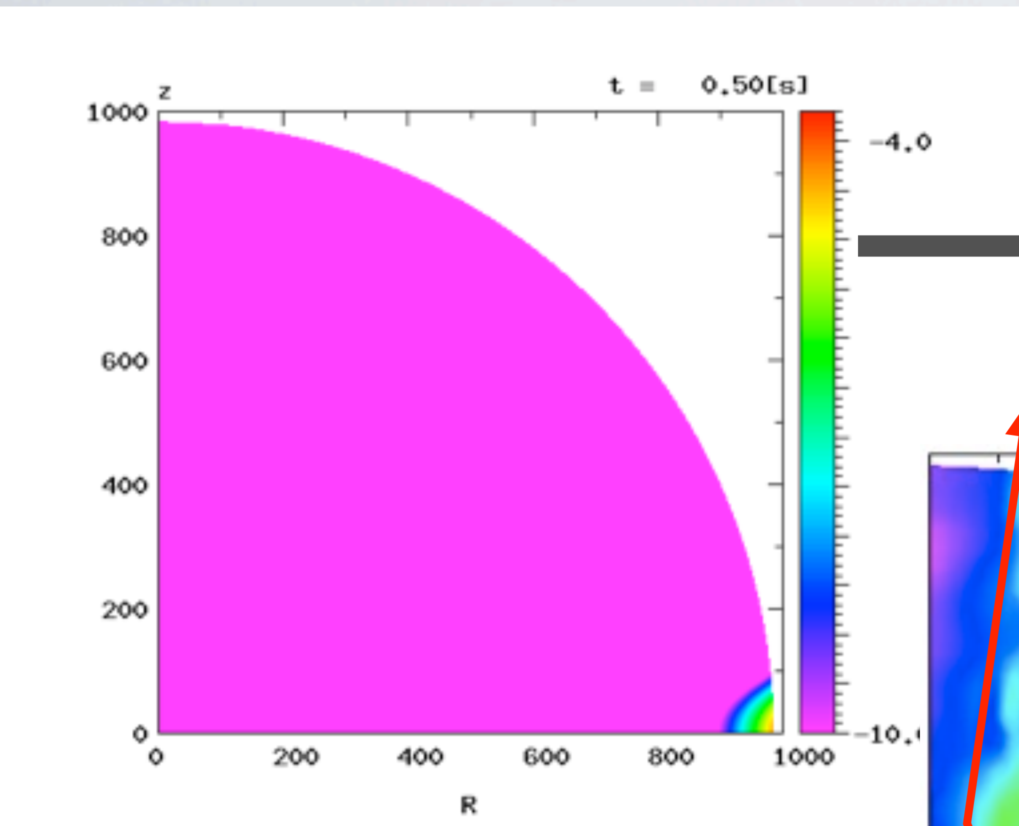
- Thus, disk luminosity is estimated as **22L$_{edd}$** for a face-on observer.

- Such apparent luminosity would increase with an increase of the mass accretion rate.

$$L_{bol} \gtrsim L_{edd}$$

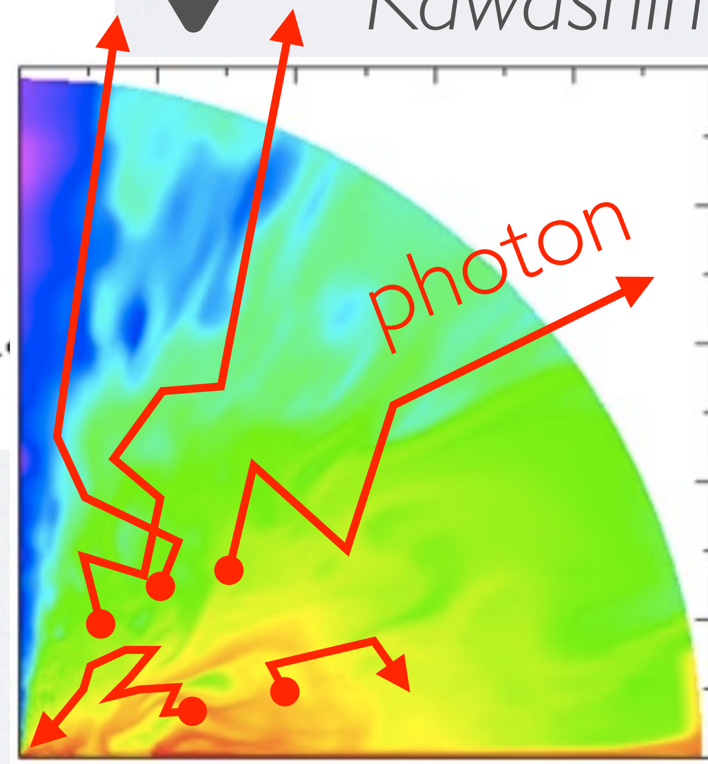
$$Mdot \sim 60\ L_{edd}/c^2$$

SPECTRA OF SUPER-EDDINGTON FLOWS

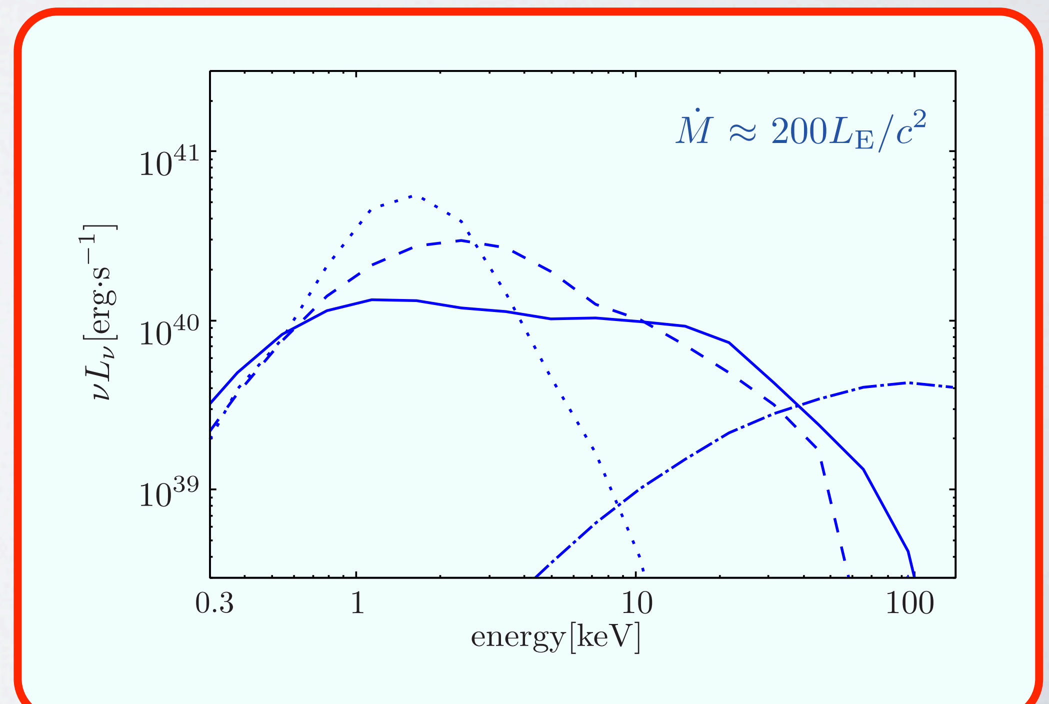


Step 1;
RHD simulation
Ohsuga et al. 2005, ApJ, 628, 368

Step2; Monte Carlo Radiation transfer
(fee-free, thermal & bulk compton)
Kawashima, Ohsuga et al. 2012

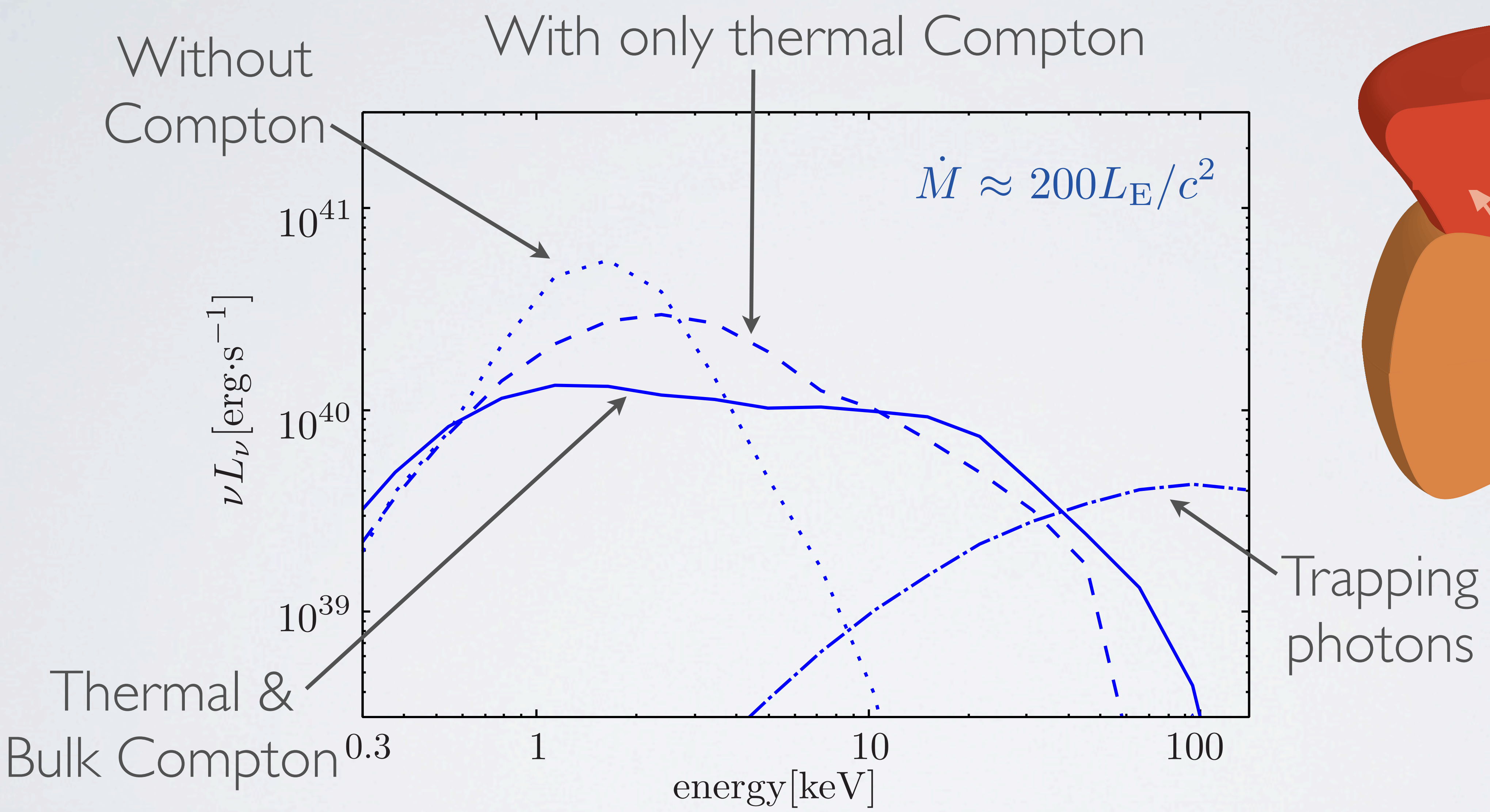


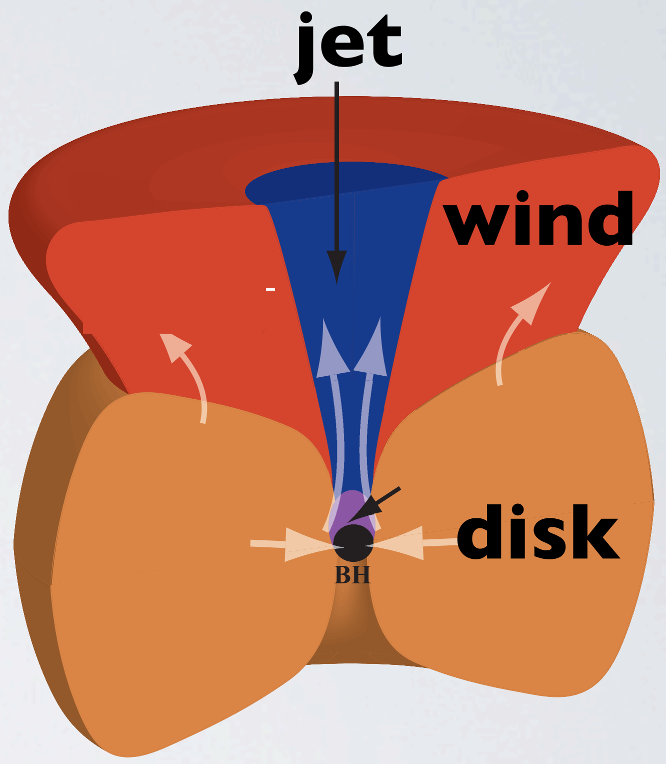
SED



Kawashima san's talk

THERMAL COMPTON AND BULK COMPTON

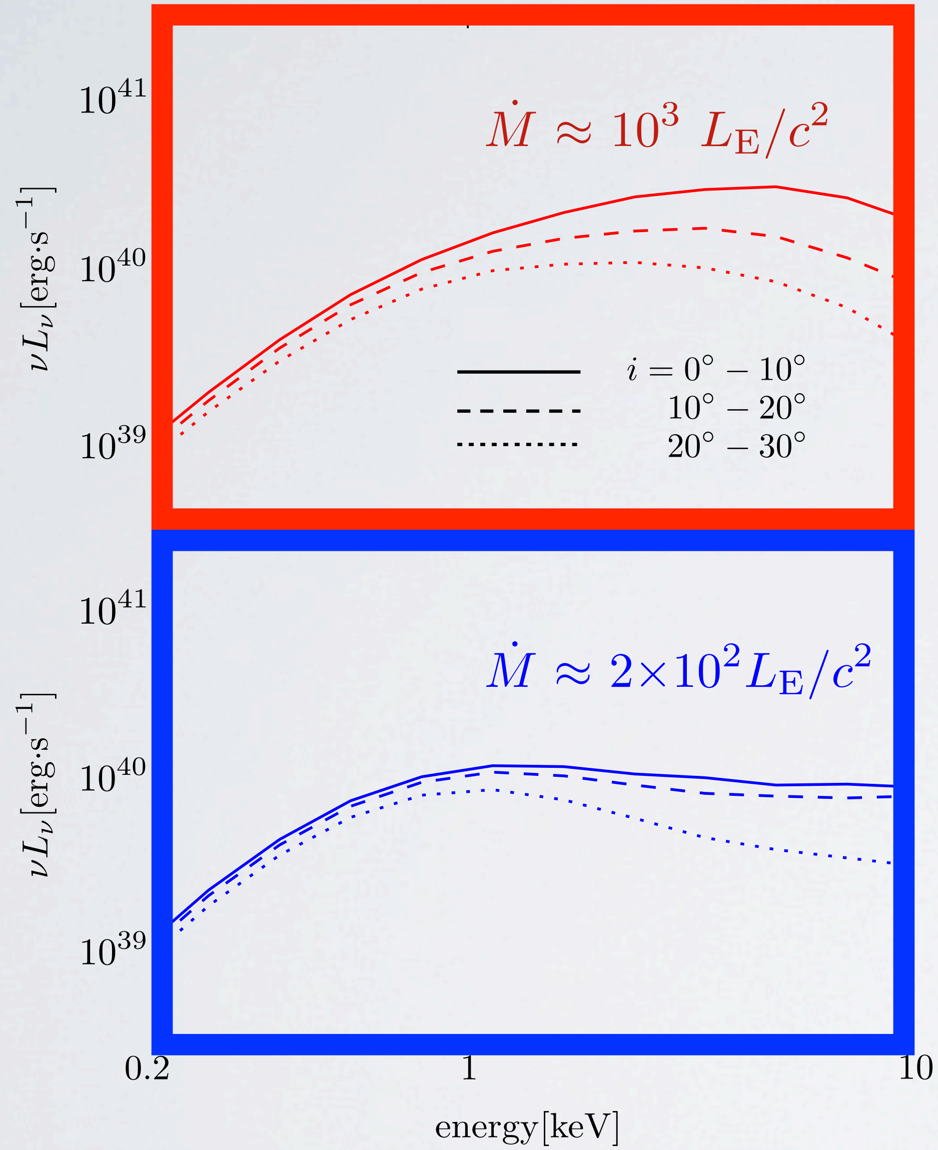




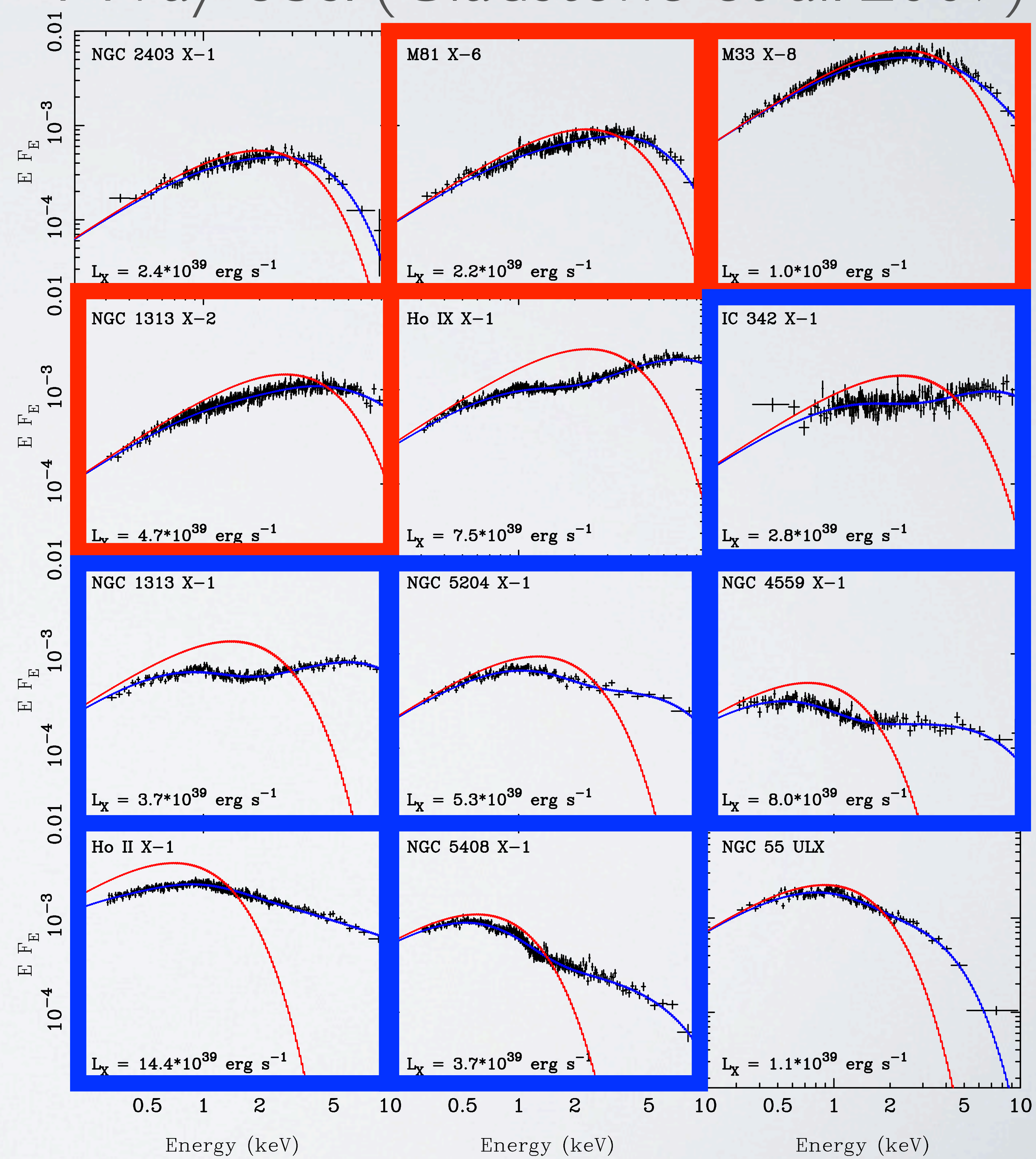
Spectra become harder by not only thermal comptonization but also bulk comptonization.

COMPARISON WITH ULXS

Simulated SED



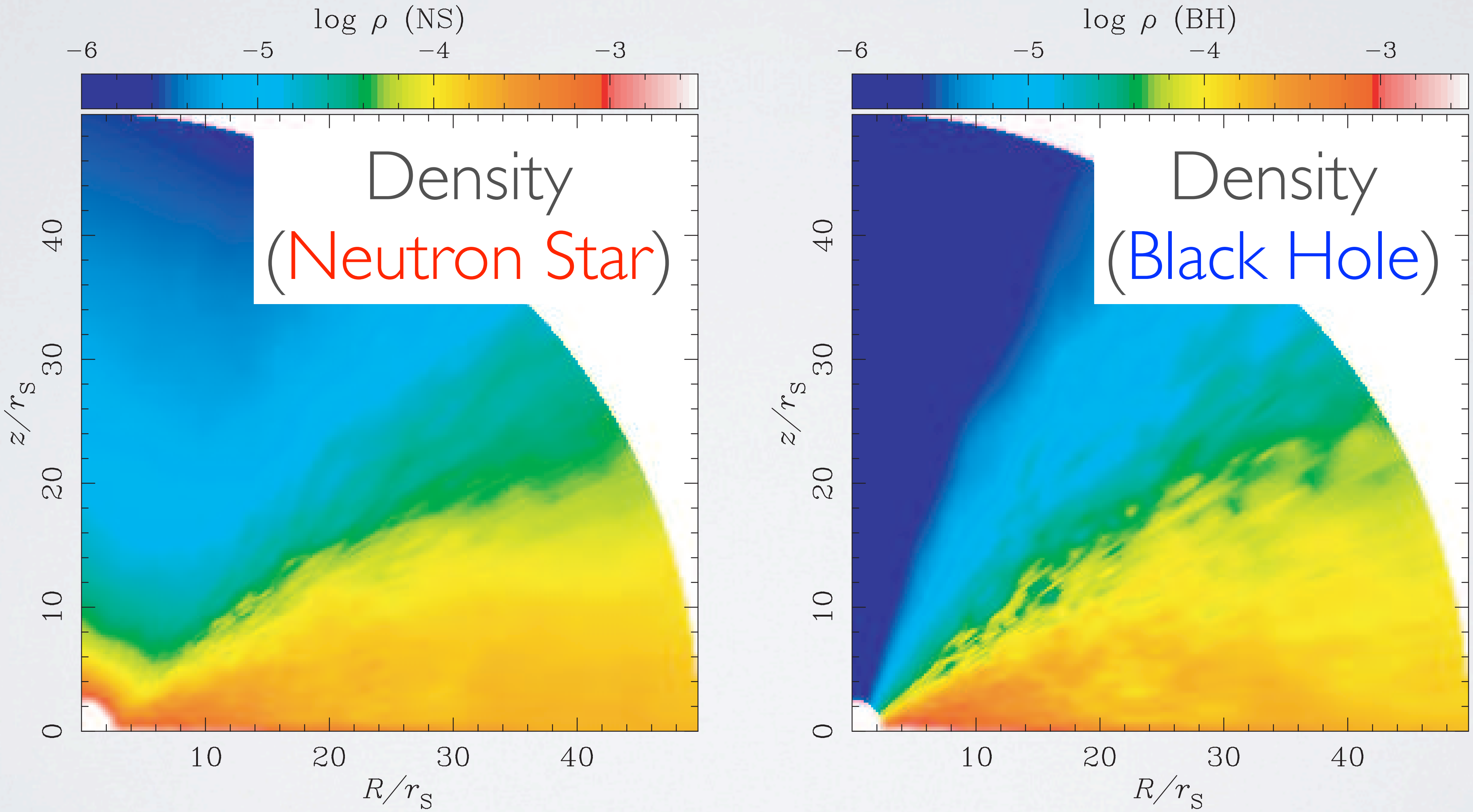
X-ray obs. (Gladstone et al. 2009)



Simulated SEDs are similar with observations.

SUPER-EDDINGTON ACCRETION ONTO NS

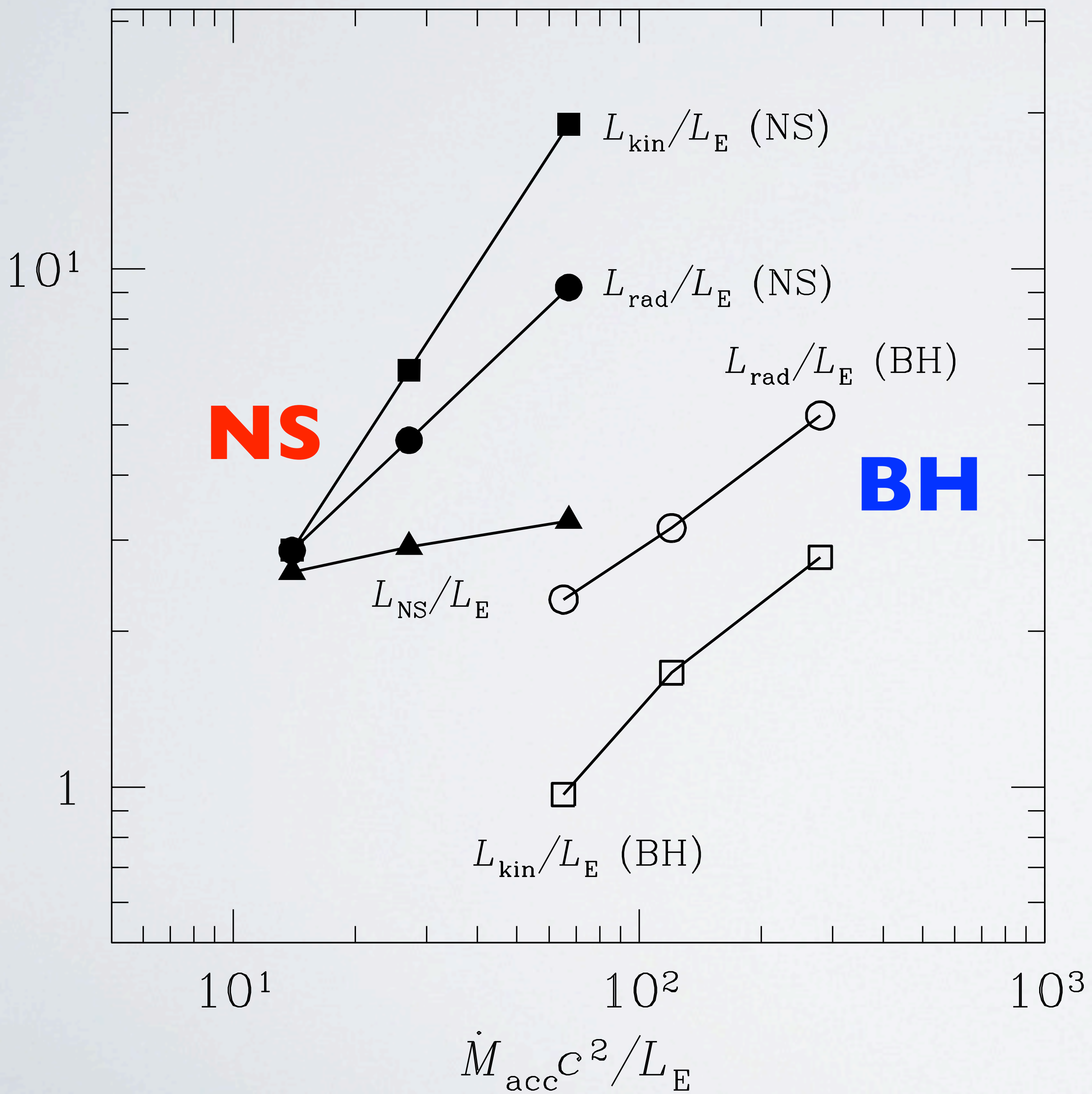
Ohsuga 2007, PASJ, 59, 1033



Super-Eddington accretion onto NSs is passible.

Shell-shaped structure forms around NSs.

NEUTRON STARS VS BLACK HOLE



- Energy conversion efficiency (L_{rad}/Mdot c^2, L_{kin}/Mdot c^2) is larger in NS case than in BH case.
- L_{rad}>L_{kin} for BH case, but L_{kin}>L_{rad} for NS case.

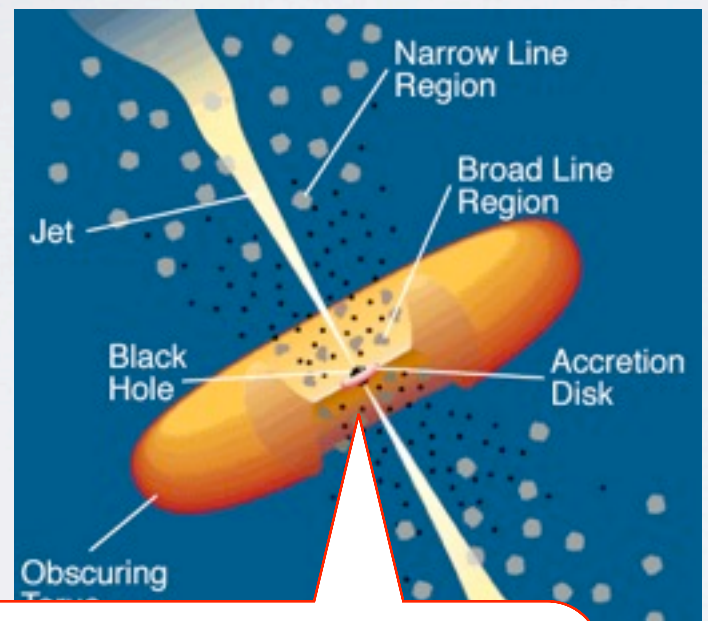
Clumpy Outflows

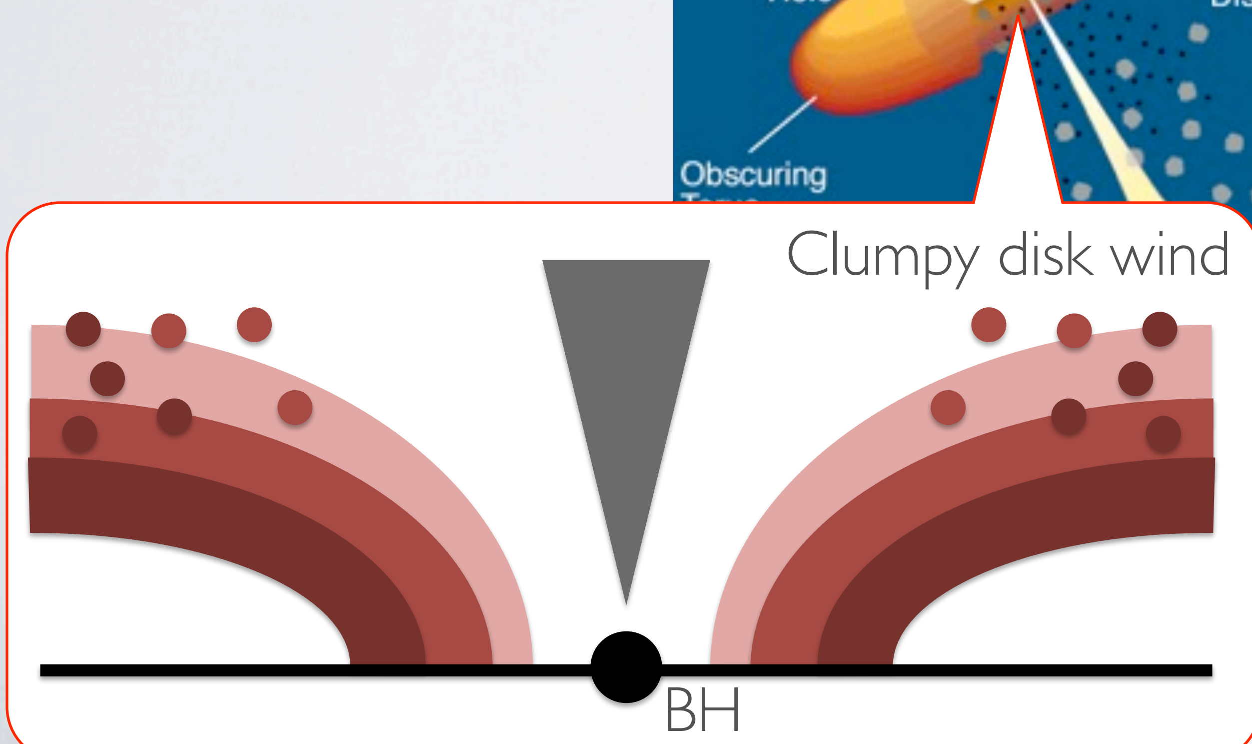
CLUMPY DISK WIND

UFOs in AGNs

Time variation of blueshifted (~0.1c) Fe absorption lines are observed in ~40% of AGNs, implying that powerful, clumpy, and high velocity outflows exist (Tombesi et al. 2010-12).

AGN

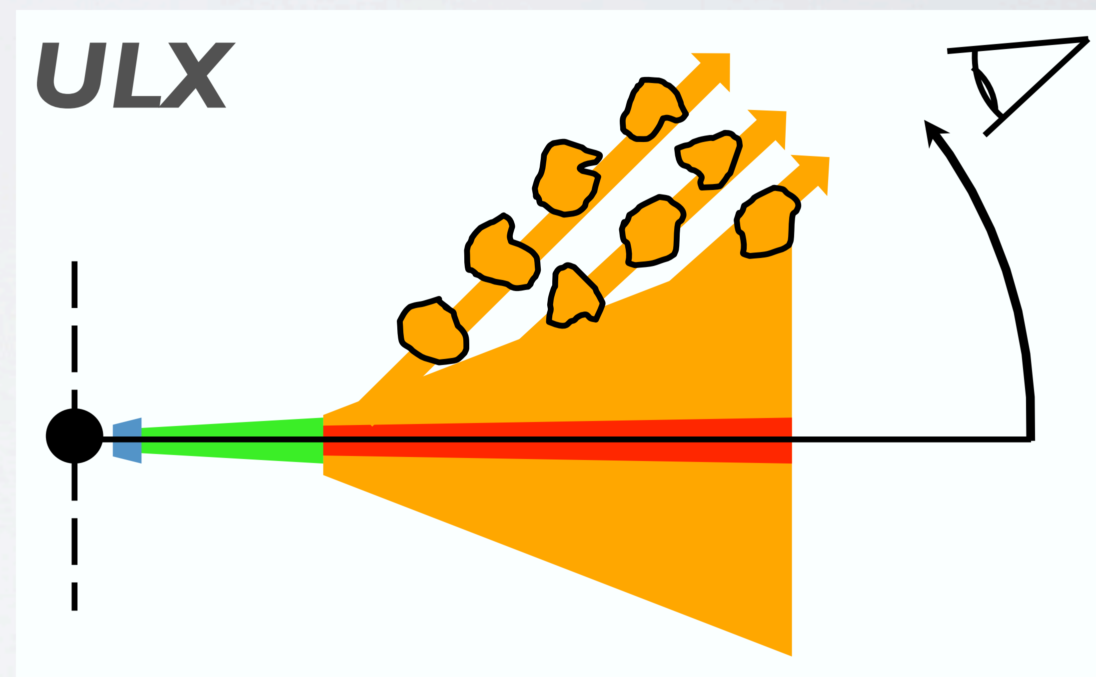




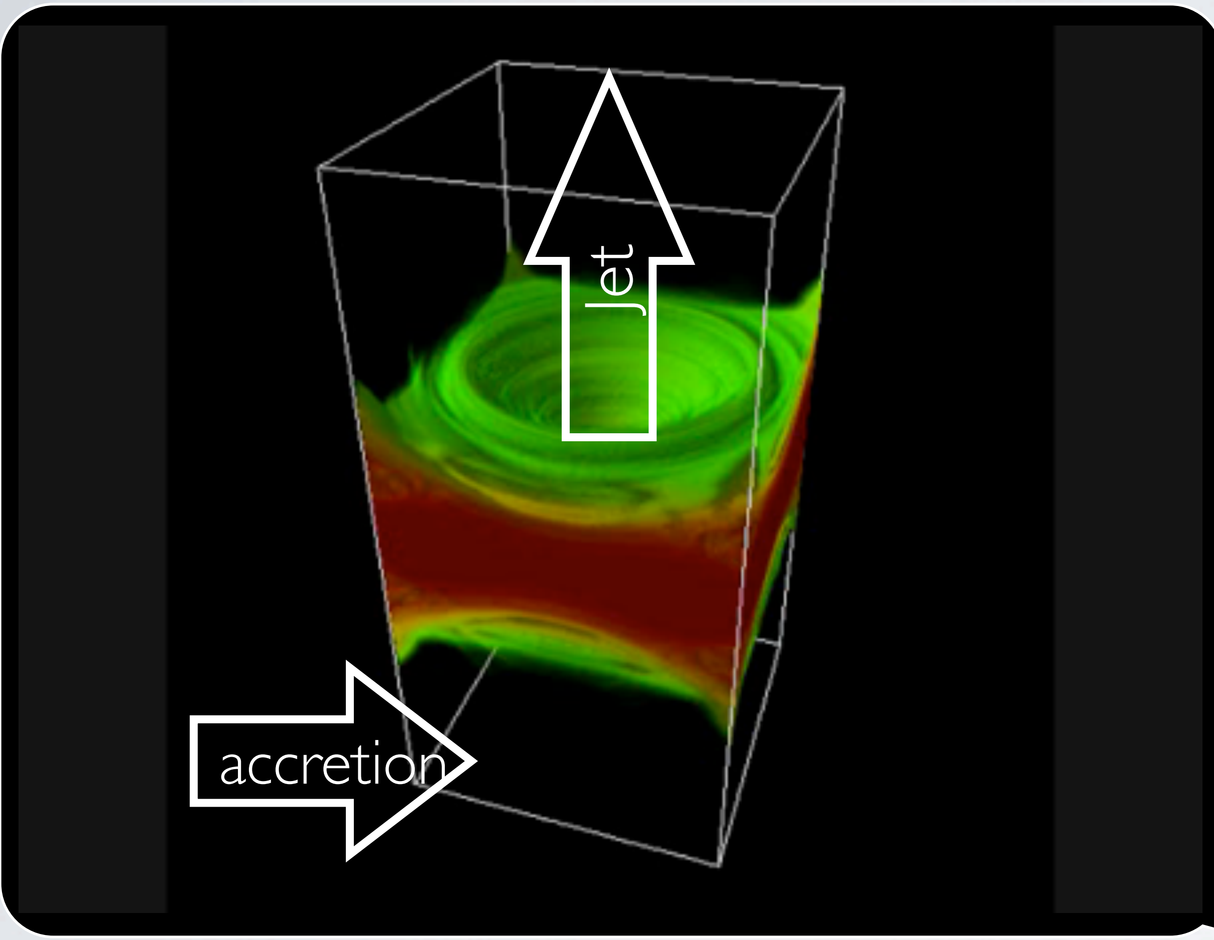
ULXs

Clumpy disk wind is suggested to explain the time variation of the ULXs.

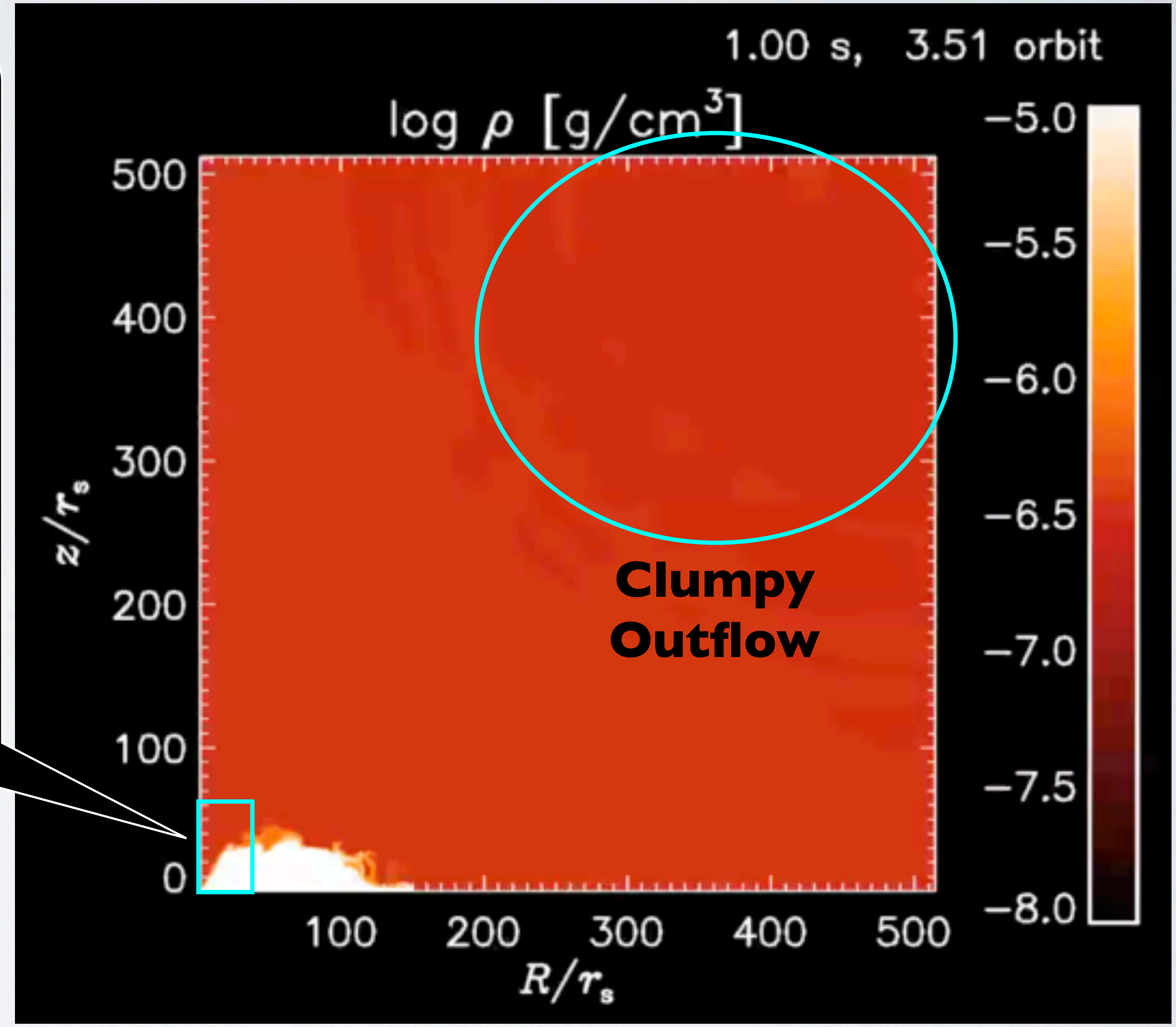
Middleton et al. 2011



INSTABILITY OF RADIATIVELY-DRIVEN DISK WIND

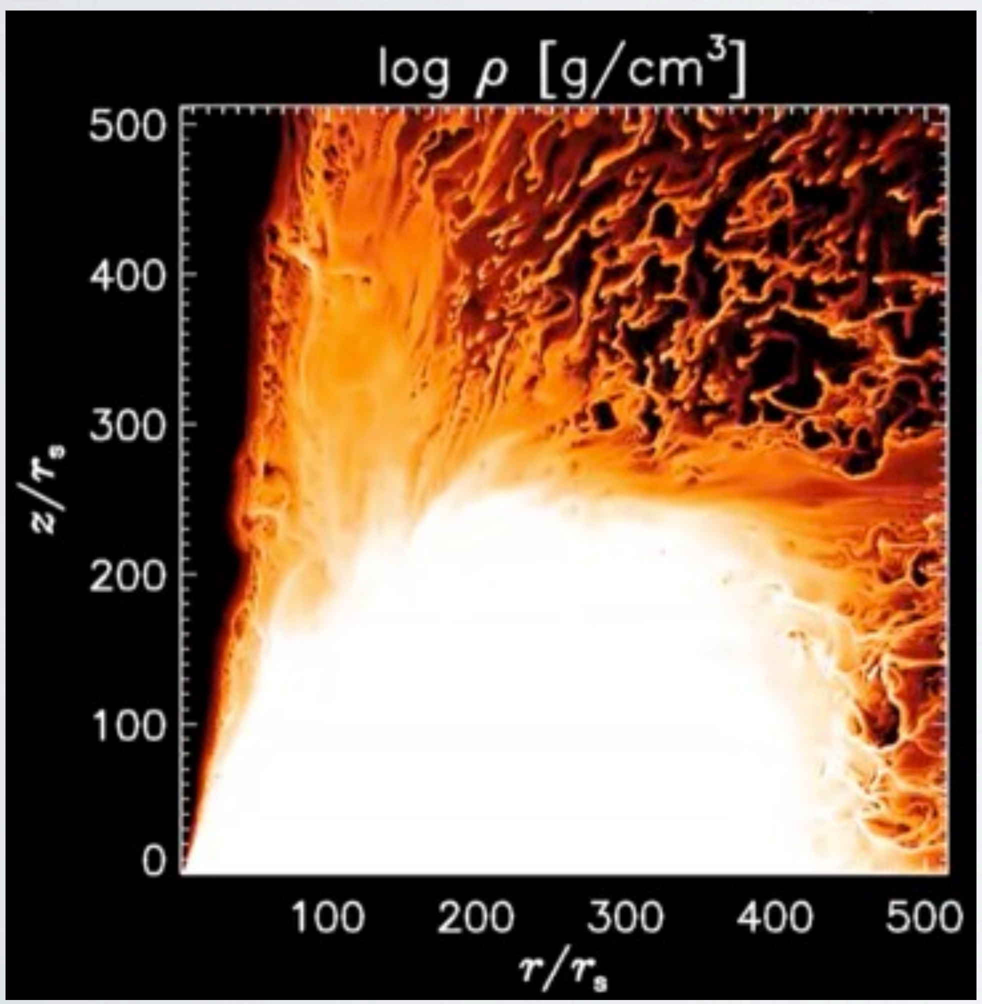


Super-Eddington disk + Radiation Pressure driven, Magnetically collimated Jet

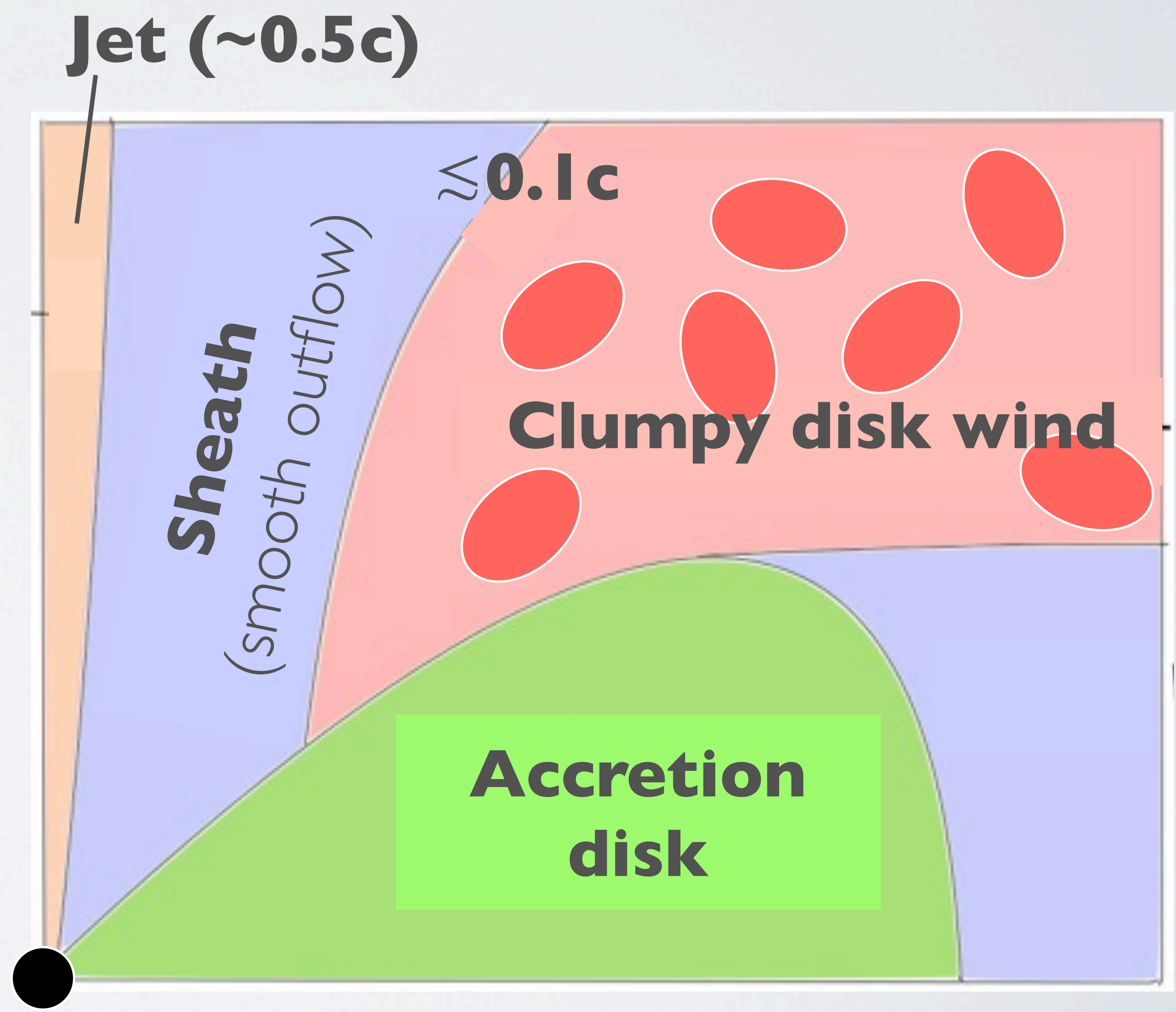


Time-dependent, Clumpy outflow with wide angle (20°~50°)

DISK, JET, & CLUMPY WIND



Schematic picture of disk-jet-clumpy wind



COMPARISON WITH OBS.

$L \gg L_{edd}$

$L \gtrsim L_{edd}$, $L \lesssim L_{edd}$

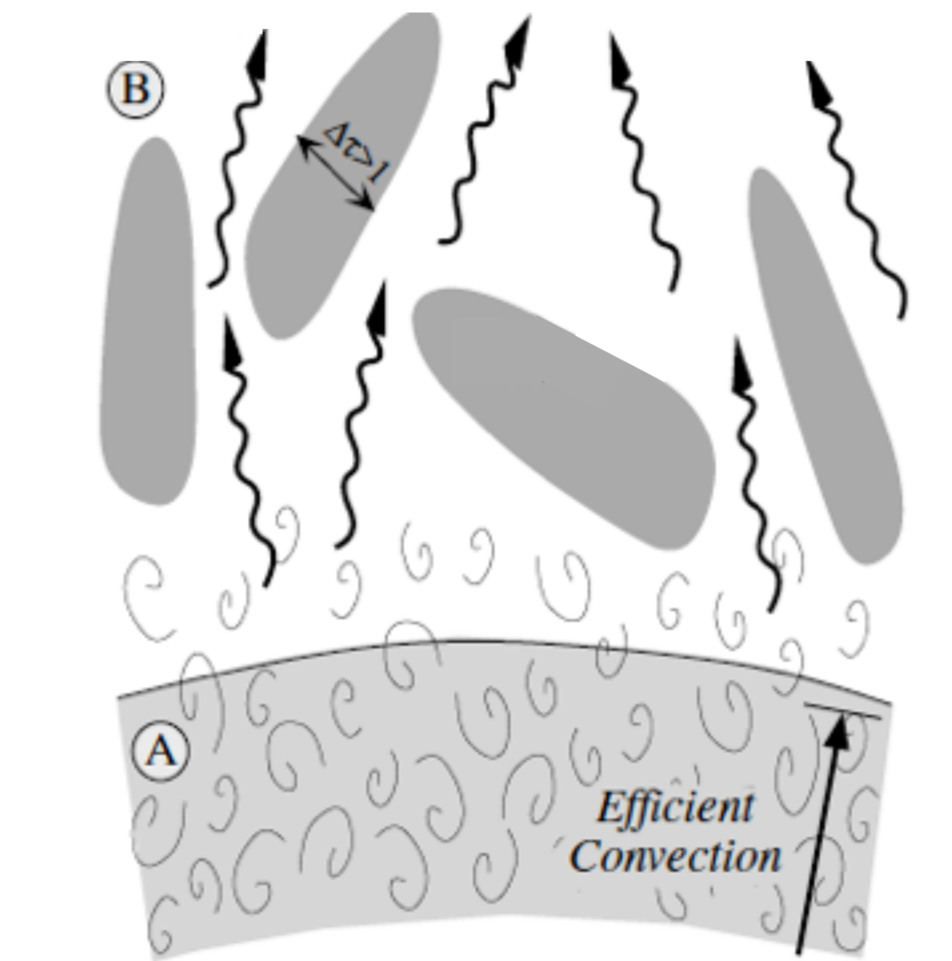
- Size of cloud
  ~ several R_S
- Column density of cloud
  ~ 10^{24}cm^{-2}
- Ionization parameter
  log(xi)~2-4
- Number of cloud (line of sight)
  $\lesssim$ 1.0
- Typical time scale
  ~ several sec (M_{BH}/10Msun)

Our clumpy winds might resolve the X-ray observations of UFOs and ULXs.

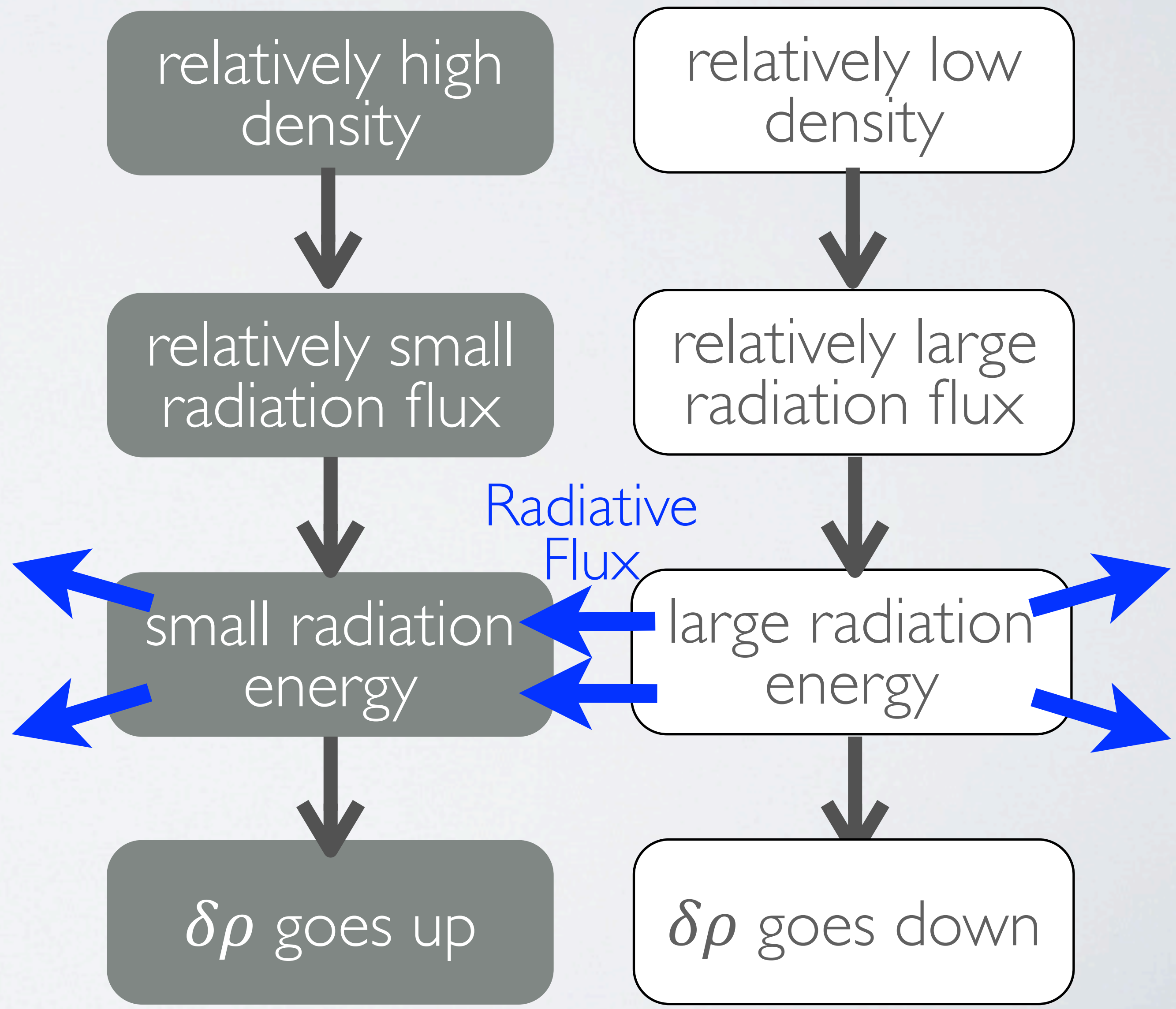
CLUMPY DISK WIND FORMS VIA SHAVIV INSTABILITY

Clumpy wind is generated via the Radiation Hydrodynamic instability (Shaviv 2001), by which matter in the radiation pressure-dominated region fragment into the clouds of $\tau \sim 1$.

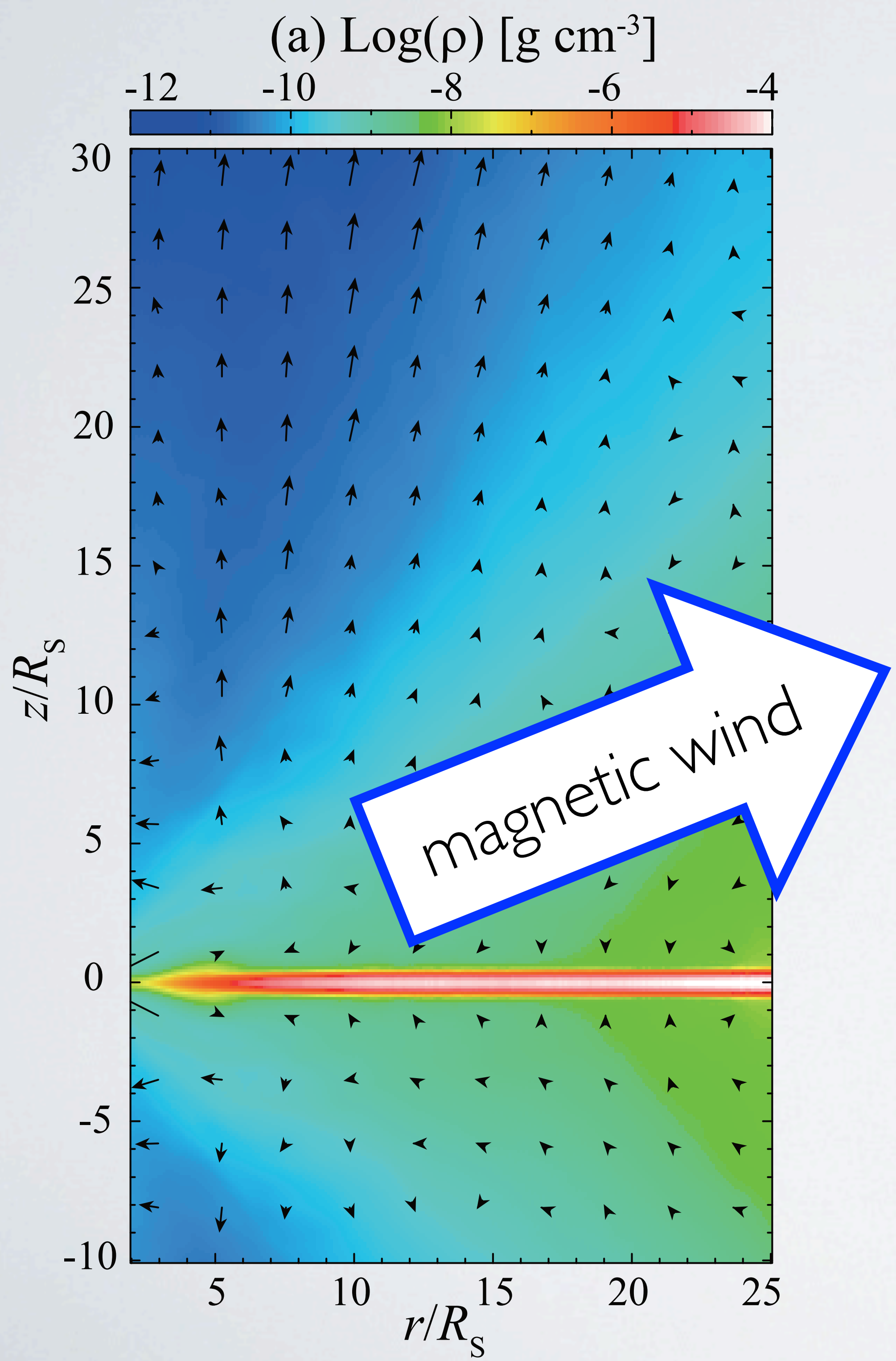
Shaviv (2001b)



cf. Shaviv 2001a; Turner+05



WIND FROM SUB-EDDINGTON DISKS



- Our Radiation-MHD simulations shows the launching the magnetic pressure-driven outflows from the standard type disks.

- We need high-resolution simulations.

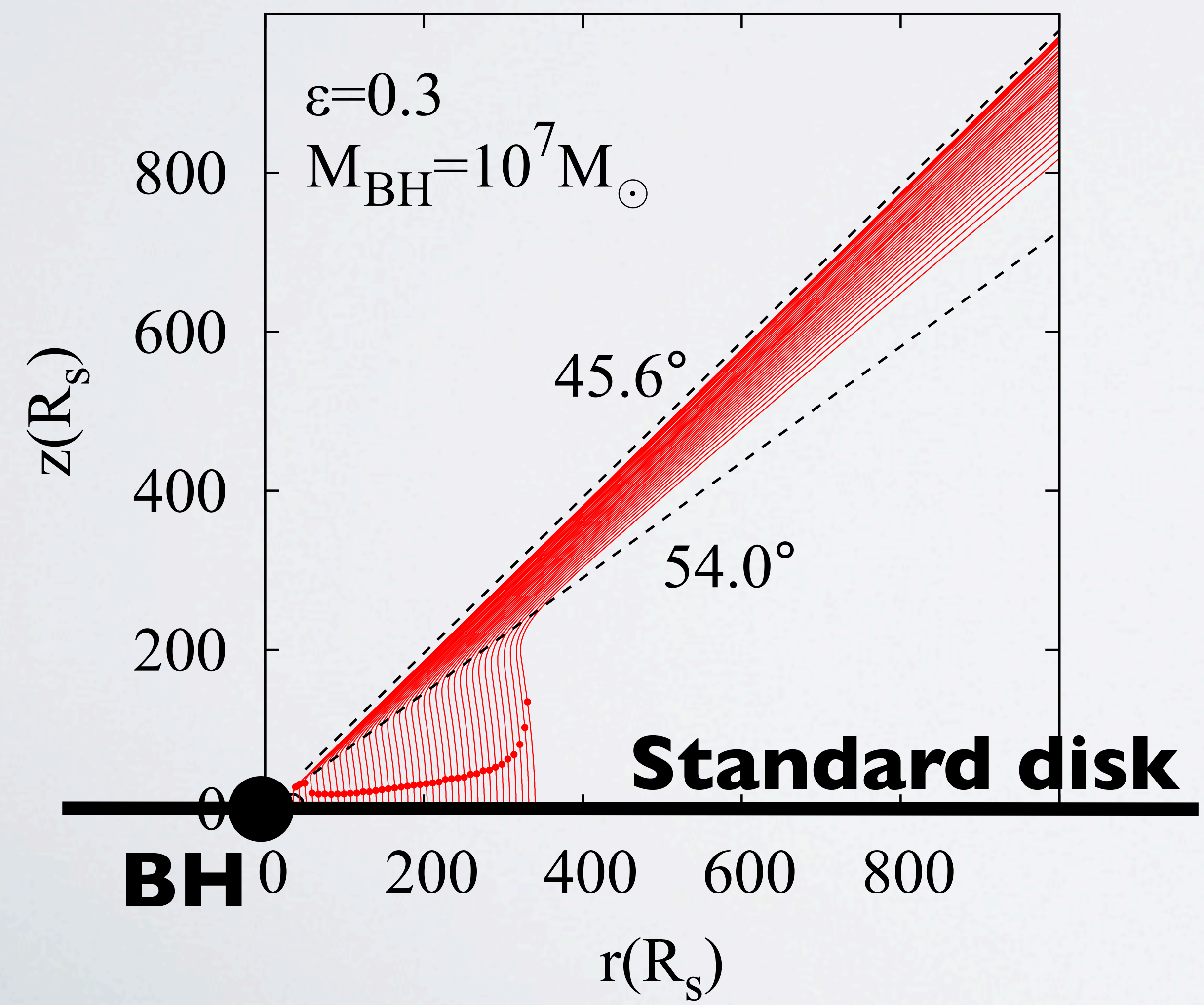
- Compton heating probably drives the thermal wind from the outer regions.

LINE DRIVEN WIND

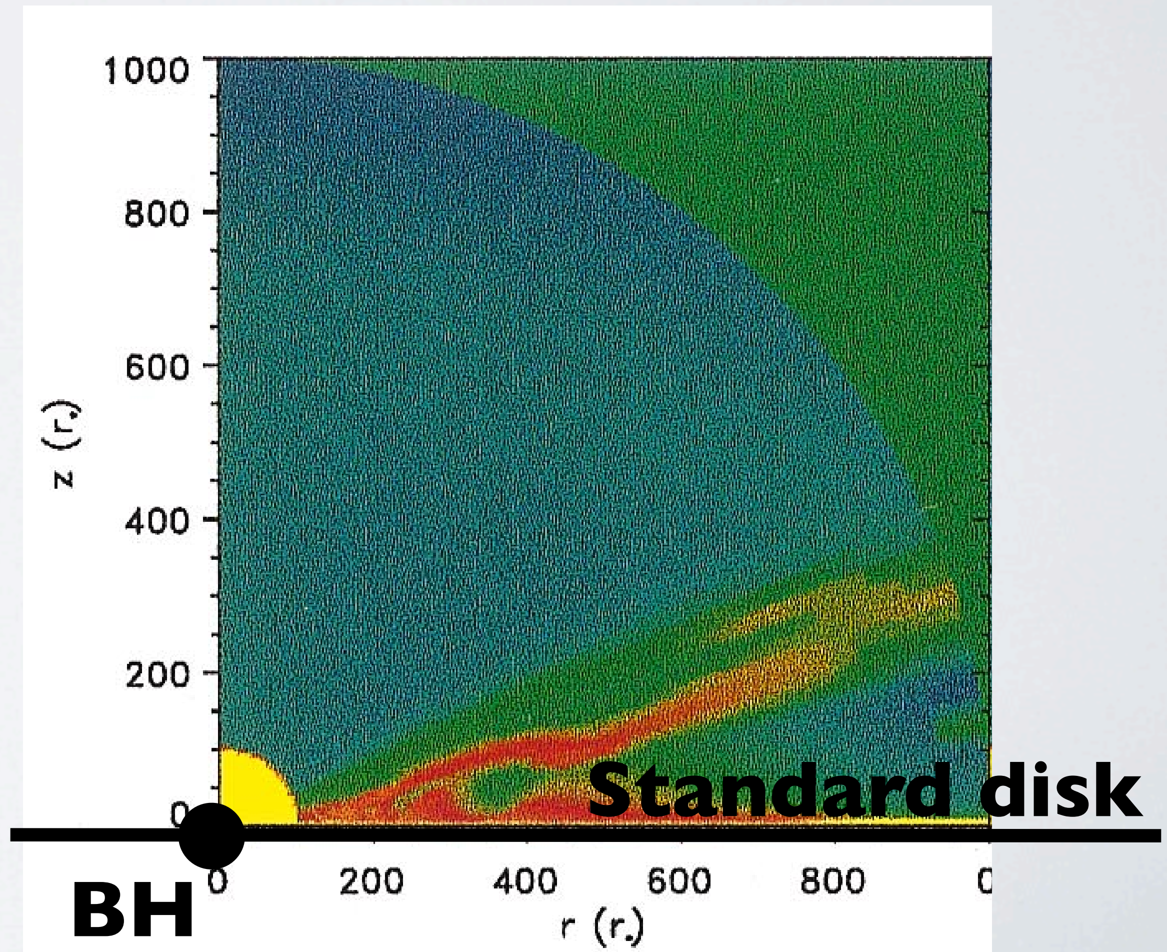
- Matter is accelerated by (UV) line absorption by metals
- X-ray works to prevent the launching the wind since the metals are over-ionized.

→Line driving is efficient for the case of super-massive BHs.

Nomura, Ohsuga, et al. submitted to PASJ

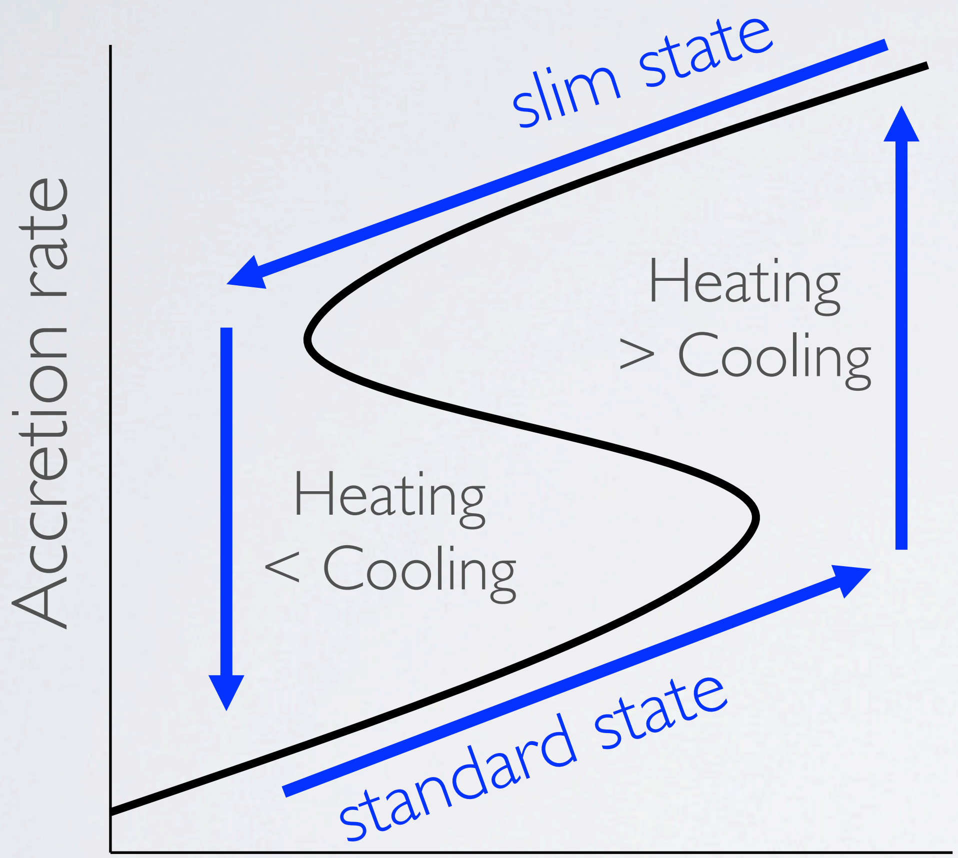


Proga et al. 2000, 2004

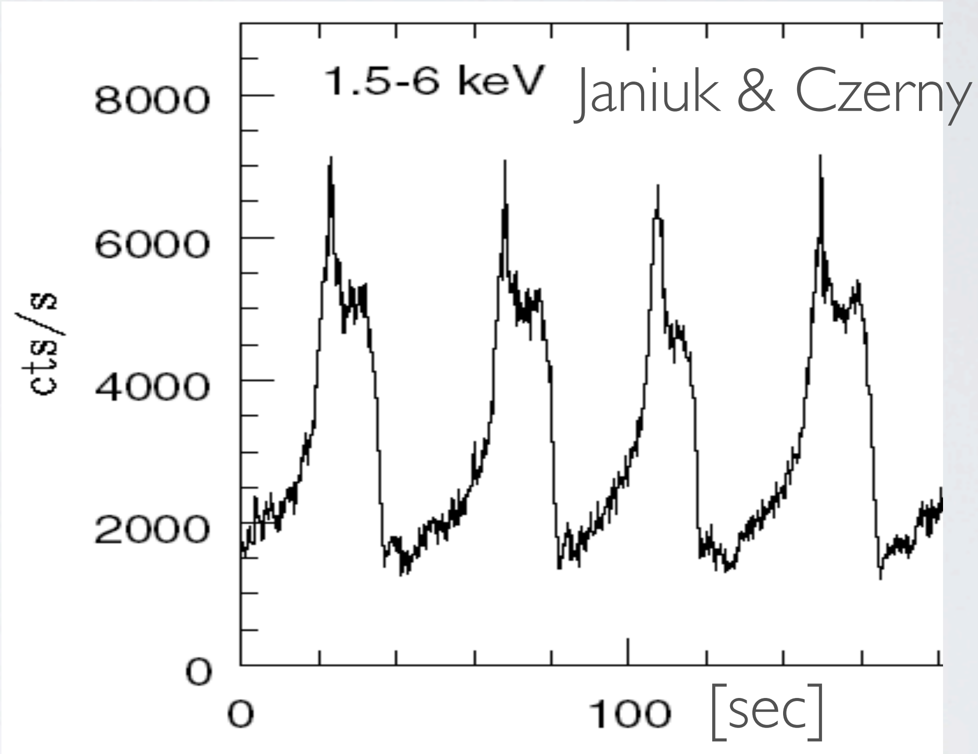


Radiation Pressure Instability

RADIATION PRESSURE INSTABILITY OF DISK



GRS1915+105

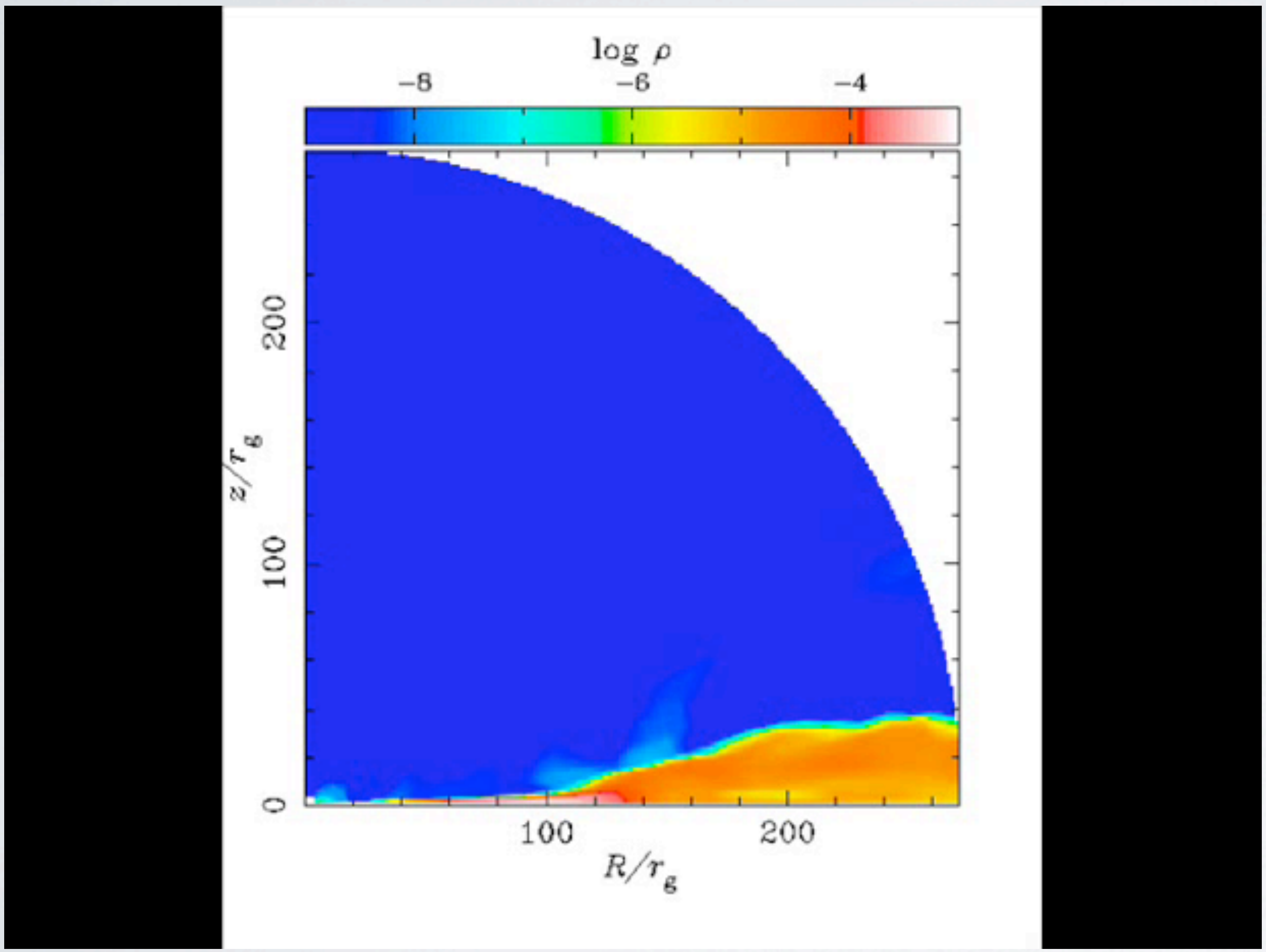


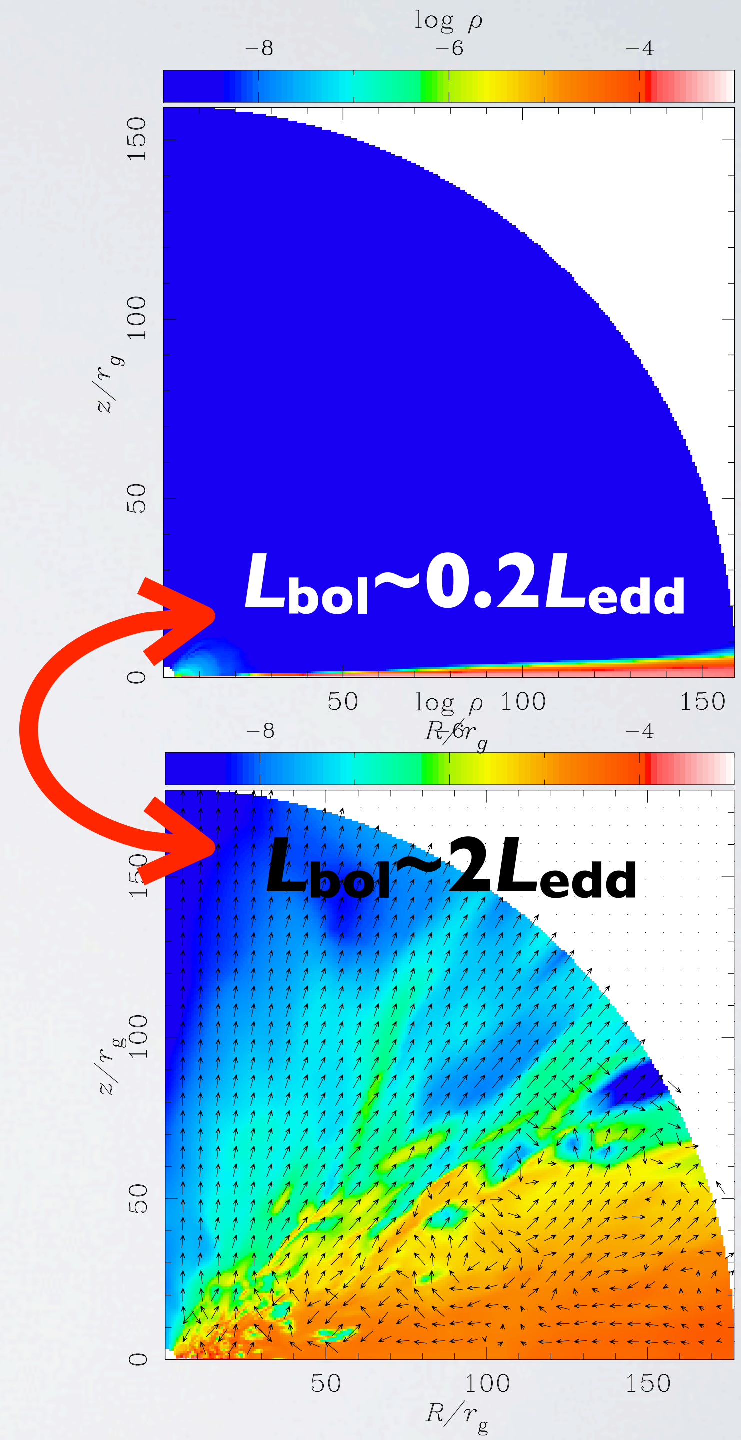
Radiation pressure-dominated disk oscillates via thermal-viscous instability.

- Disk Luminosity goes up and down. $2L_{\mathrm{Edd}} \rightleftarrows 0.3L_{\mathrm{Edd}}$ (Yamaoka et al.)
- Timescale ~ 40sec
- Jet intermittently appears

LIMIT-CYCLE (RADIATION-HD)

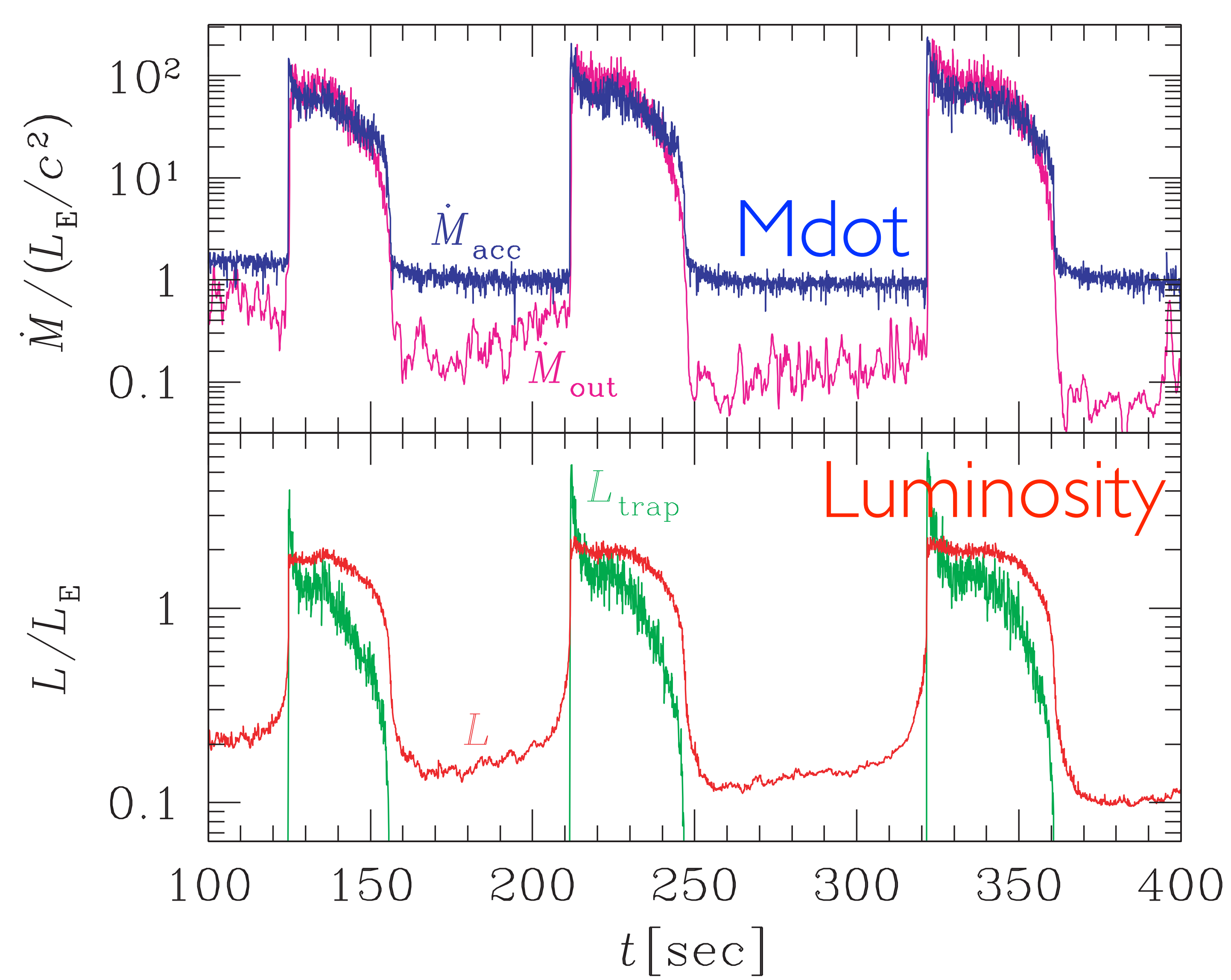
Ohsuga 2006, ApJ, 640, 923





Thermal viscous instability induces limit-cycle behavior.

LIMIT-CYCLE OSCILLATION



Our simulations nicely fit the observations of microquasar, GRS1915+105 (yamaoka et al. 2001, see alo Janiuk & Czerny 2005).

1. Luminosity variation
   $2L_{edd} \leftrightarrow 0.2L_{edd}$
2. Timescale ~ 40 sec.
3. Intermittent outflow.

CONC. & FUTURE WORK

- We succeeded in reproducing three distinct accretion modes (slim disk, standard disk, RIAF) and outflows by radiation-MHD simulations.
- Radiatively-driven, magnetically collimated jets and clumpy disk winds are launched from the super-Eddington disks.
- Limit-cycle oscillations are reproduced by radiation-HD simulations. We should confirm by radiation-MHD simulations.
- 3D relativistic radiation-MHD simulations (without FLD app.) is left as important future work (POSTER by Takahashi et al.).