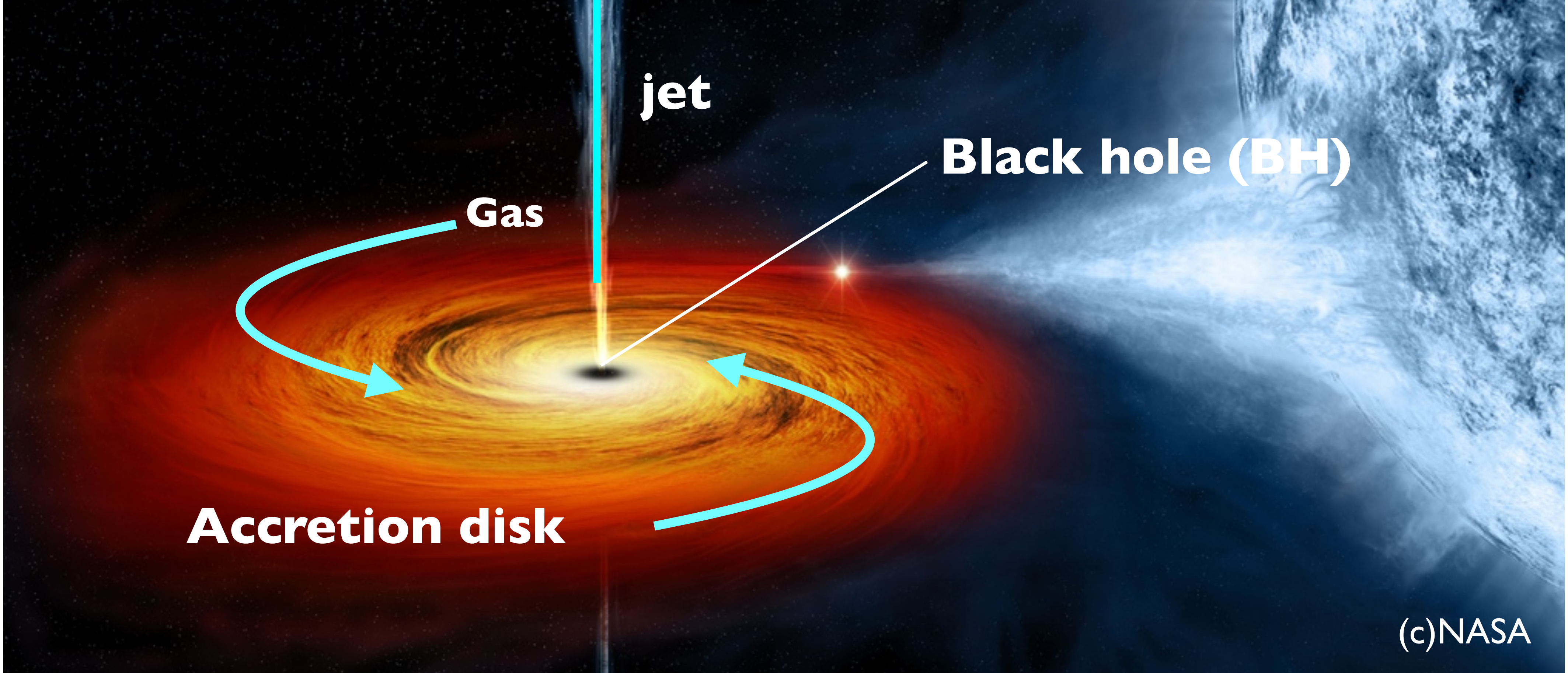
Active Galactic Nucleus Jets in the Event Horizon Telescope Era

BH HIGH-POWER ACCRETION & OUTFLOW



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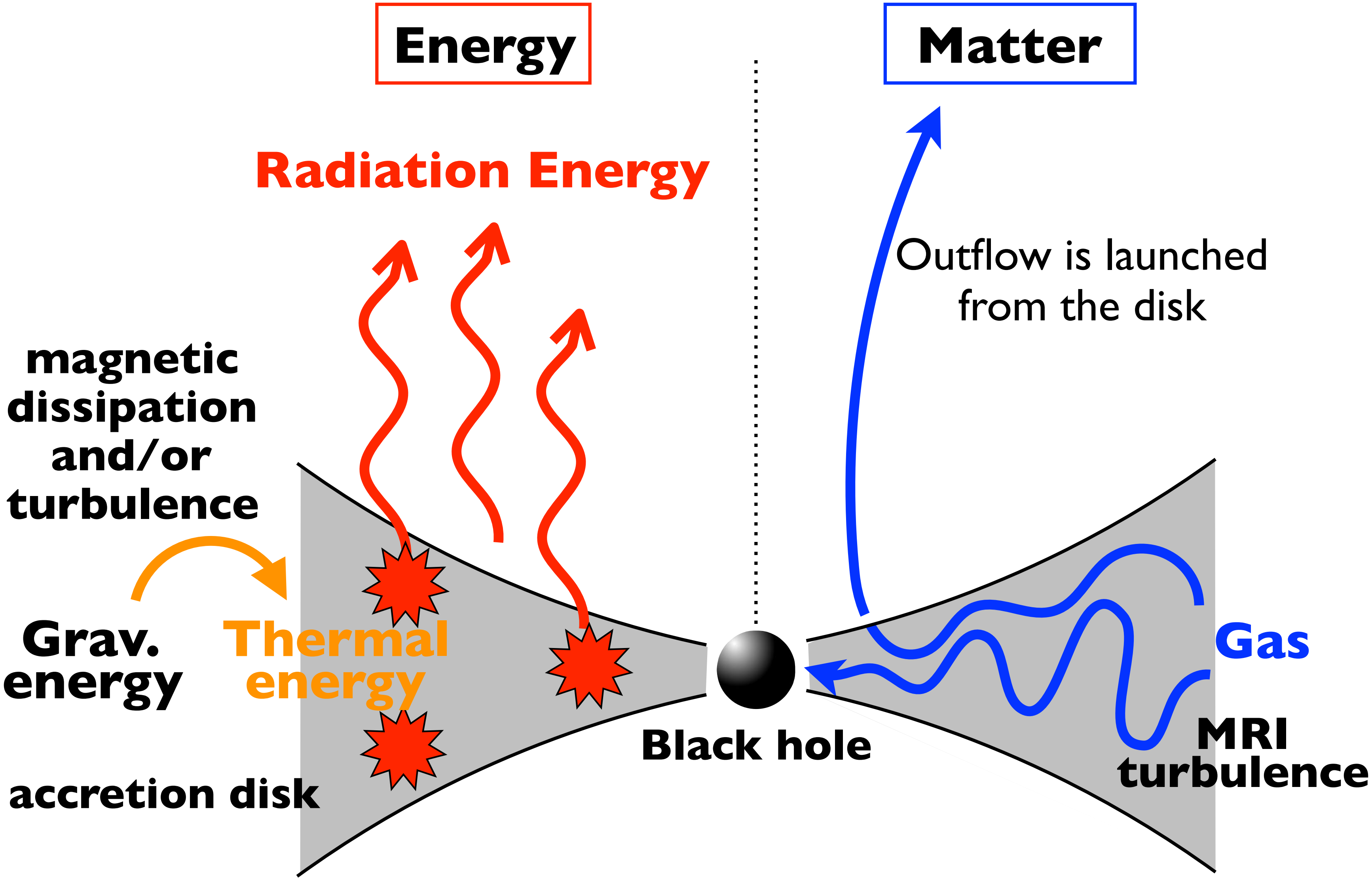
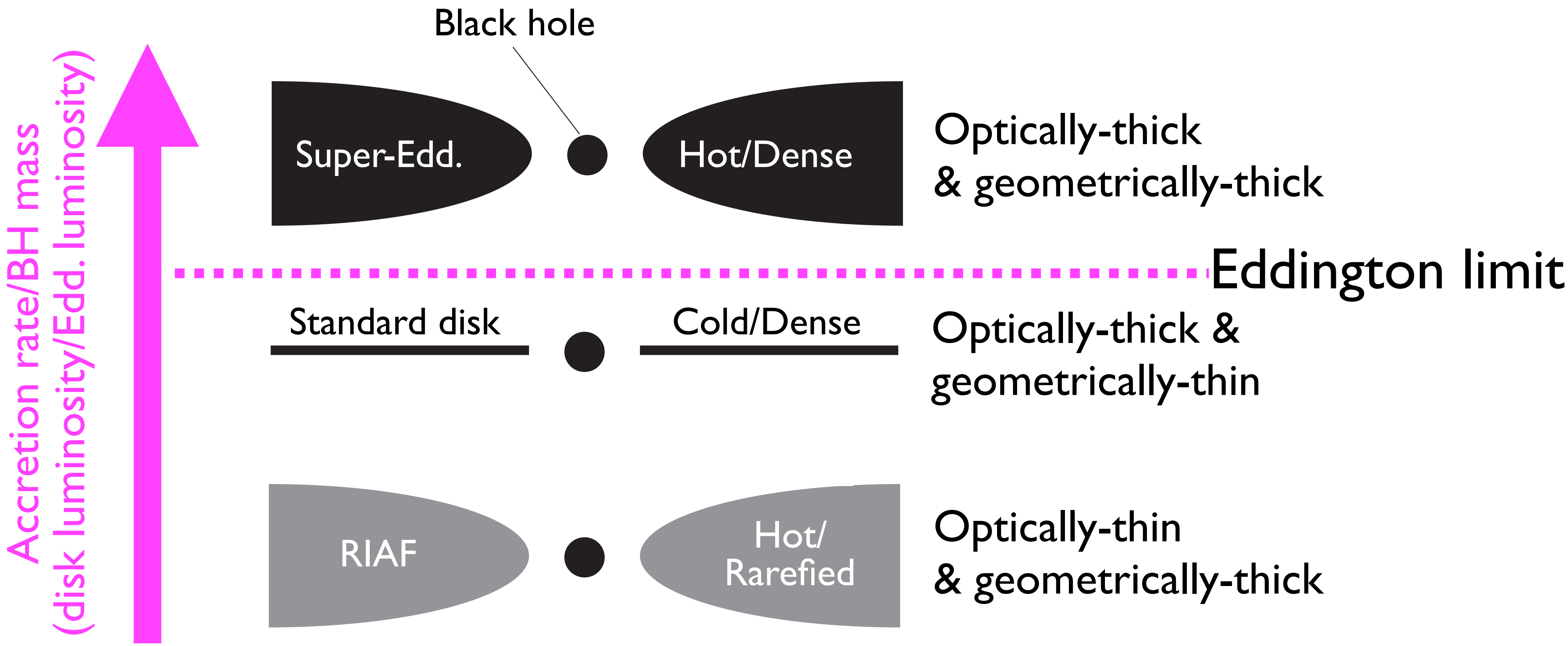
Role of Radiation and Magnetic Fields



Three Accretion Modes

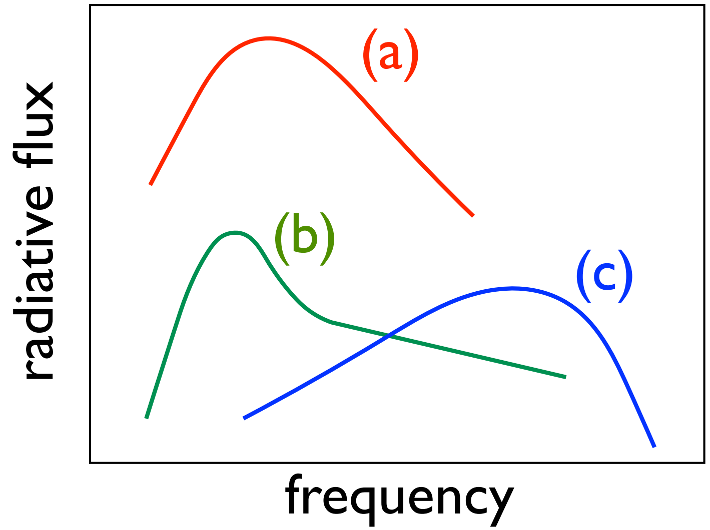
Shakura & Sunyaev 73; Ichimaru 77; Abramowicz+ 88; Narayan & Yi 94;



Accretion disks are divided into three modes by depending on the accretion rate (disk luminosity)

Three Accretion Modes

Spectra (schematic)

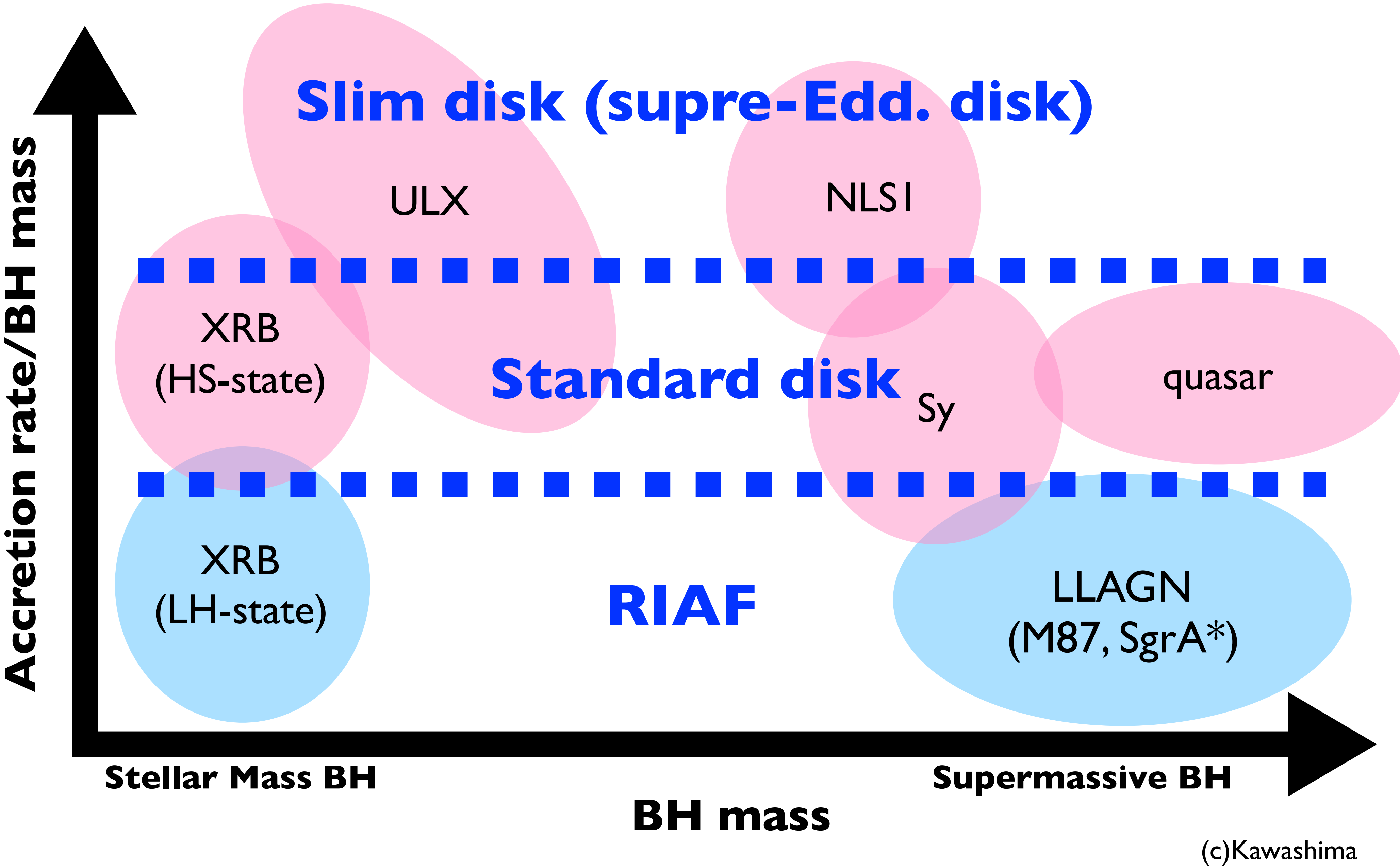


Different spectral states imply the existence of different accretion modes

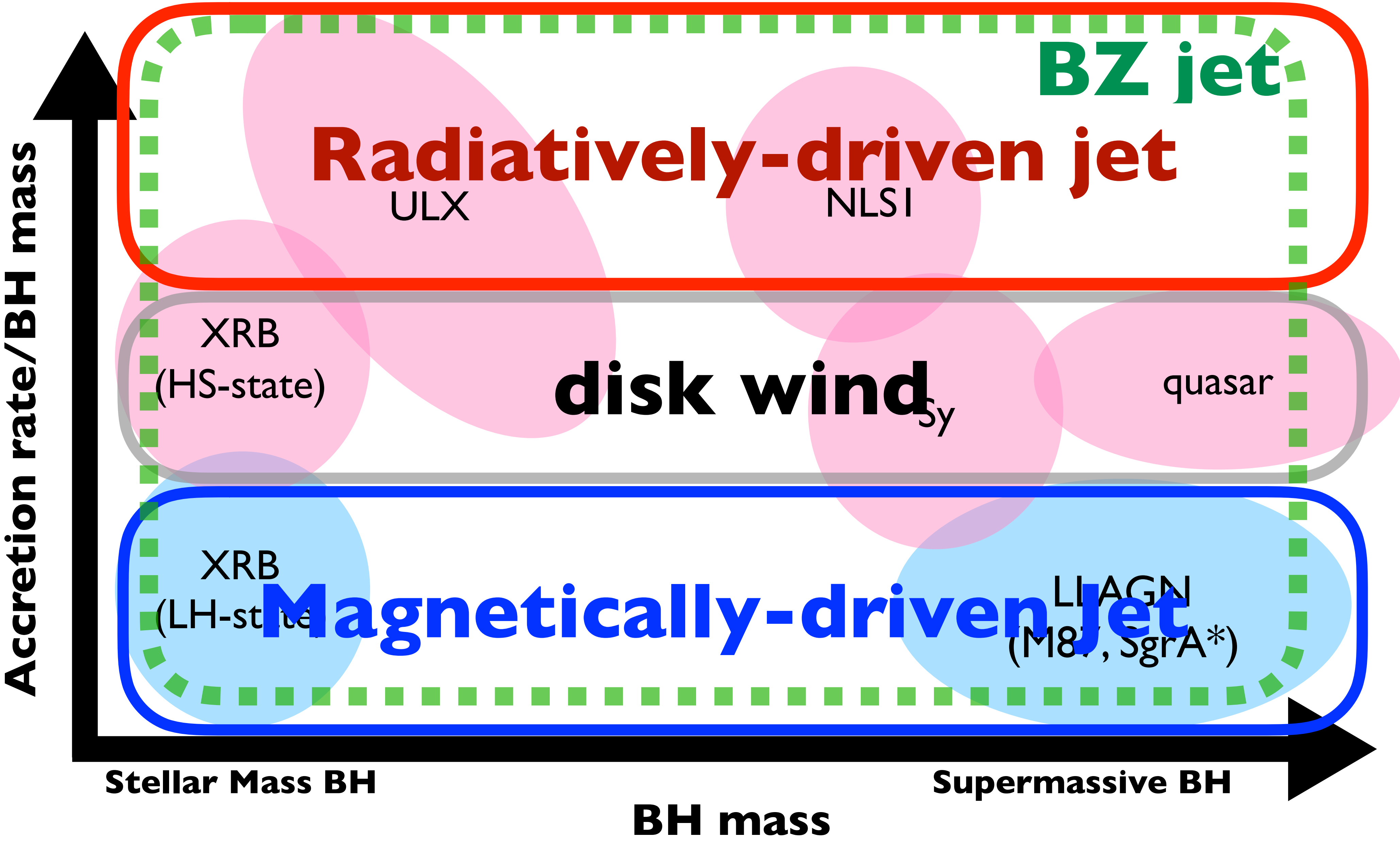
Mass accretion rate
(disk luminosity)

	(a)Slim disk	(b)Standard disk	(c)RIAF/ADAF
			
Temperature (10Msun)	~10^8K	~$10^{6\text{-}7}$K	10^9K
Optical thickness	thick	thick	thin

BH mass vs Accretion rate

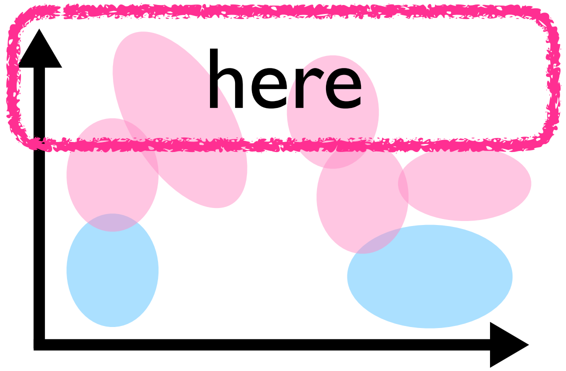


BH mass vs Accretion rate



Modified version of Kawashima-san's slikde

Radiation-MHD Simulations



Magnet Fields;

(1)Angular momentum is transported by the Magneto rotational instability (MRI), leading to the **mass accretion** onto BHs.

(2)**Jets** are accelerated by the Lorentz force.

Radiation Fields;

(1)Disk loses the energy by emitting photons (**cooling**).

(2)**Jets** are launched via the Radiation force.

General Relativity;

(1)BH gravity is described by General Relativity.

(2)Effect of rotating BHs cannot be treated by Newtonian Mechanics

Basic Equations of GR Radiation-MHD

MHD

mass cons. $\partial_t \left(\sqrt{-g}\rho u^t\right) + \partial_i \left(\sqrt{-g}\rho u^i\right) = 0$

Gas-Radiation interaction

Gauss's law $\partial_i \left(\sqrt{-g}B^i\right) = 0$

Induction eq. $\partial_t \left(\sqrt{-g}B^i\right) = -\partial_j \left[\sqrt{-g}\left(b^j u^i - b^i u^j\right)\right]$

energy momentum cons. for MHD $\partial_t \left(\sqrt{-g}T^t_\nu\right) + \partial_i \left(\sqrt{-g}T^i_\nu\right) = \sqrt{-g}T^\kappa_\lambda \Gamma^\lambda_{\nu\kappa} + \sqrt{-g}G_\nu$

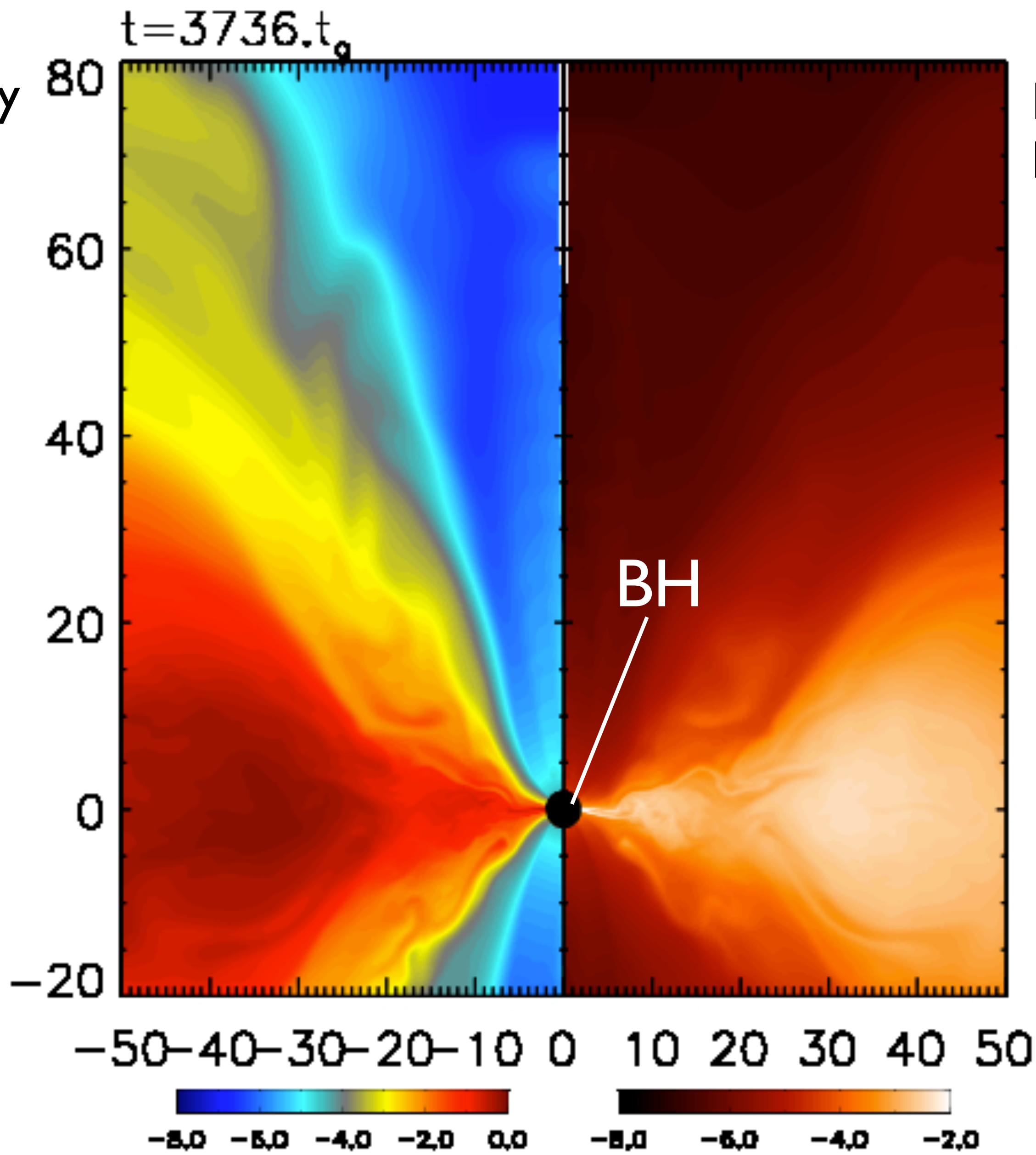
energy momentum cons. for radiation $\partial_t \left(\sqrt{-g}R^t_\nu\right) + \partial_i \left(\sqrt{-g}R^i_\nu\right) = \sqrt{-g}R^\kappa_\lambda \Gamma^\lambda_{\nu\kappa} - \sqrt{-g}G_\nu$

RADIATION

We use Kerr-shild metric

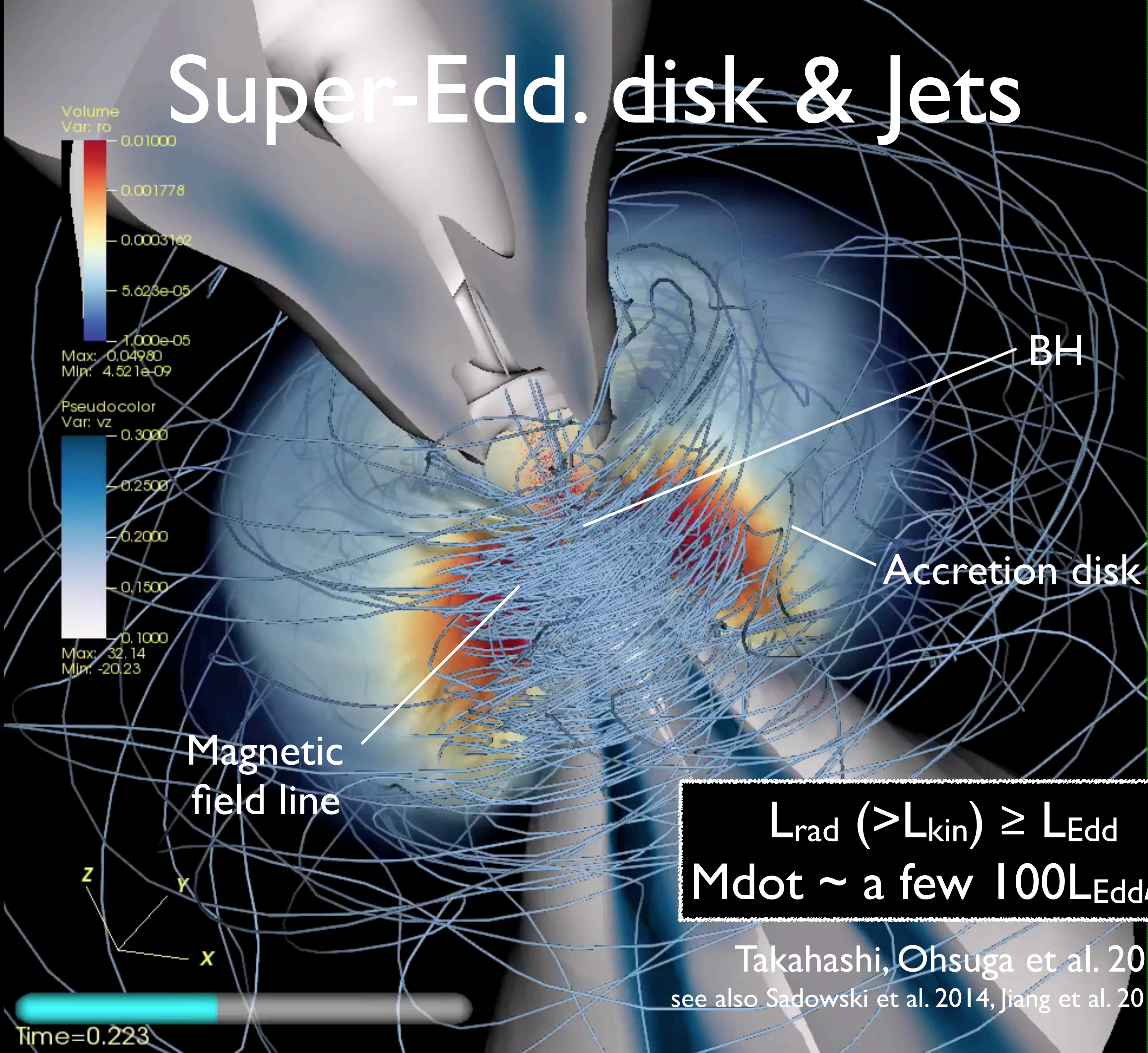
Super-Edd. disk & Jets

Gas Density



Radiation
Energy density

Super-Edd. disk & Jets



L_{rad} ($>L_{kin}$) $\geq L_{Edd}$

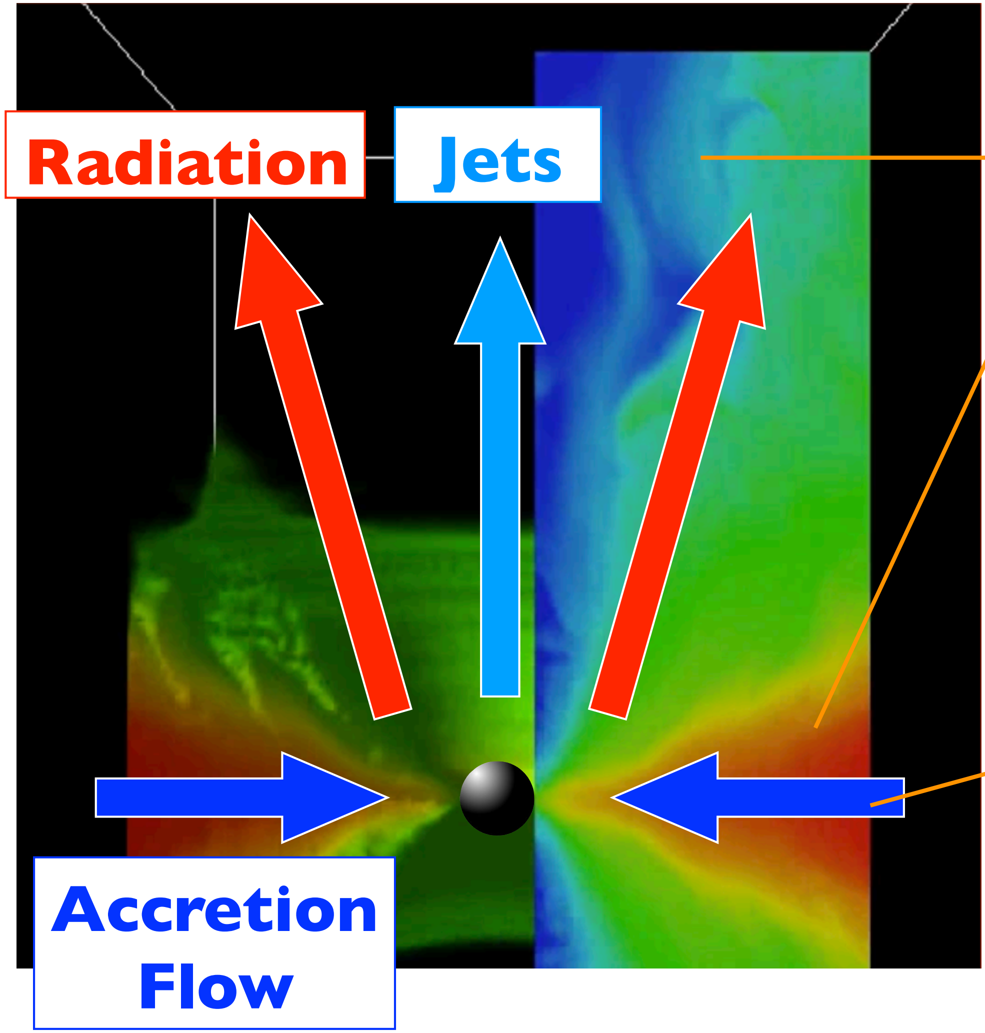
Mdot ~ a few $100L_{Edd}/c^2$

Takahashi, Ohsuga et al. 2016

see also Sadowski et al. 2014, Jiang et al. 2014

Super-Edd. disk & radiatively-driven jets

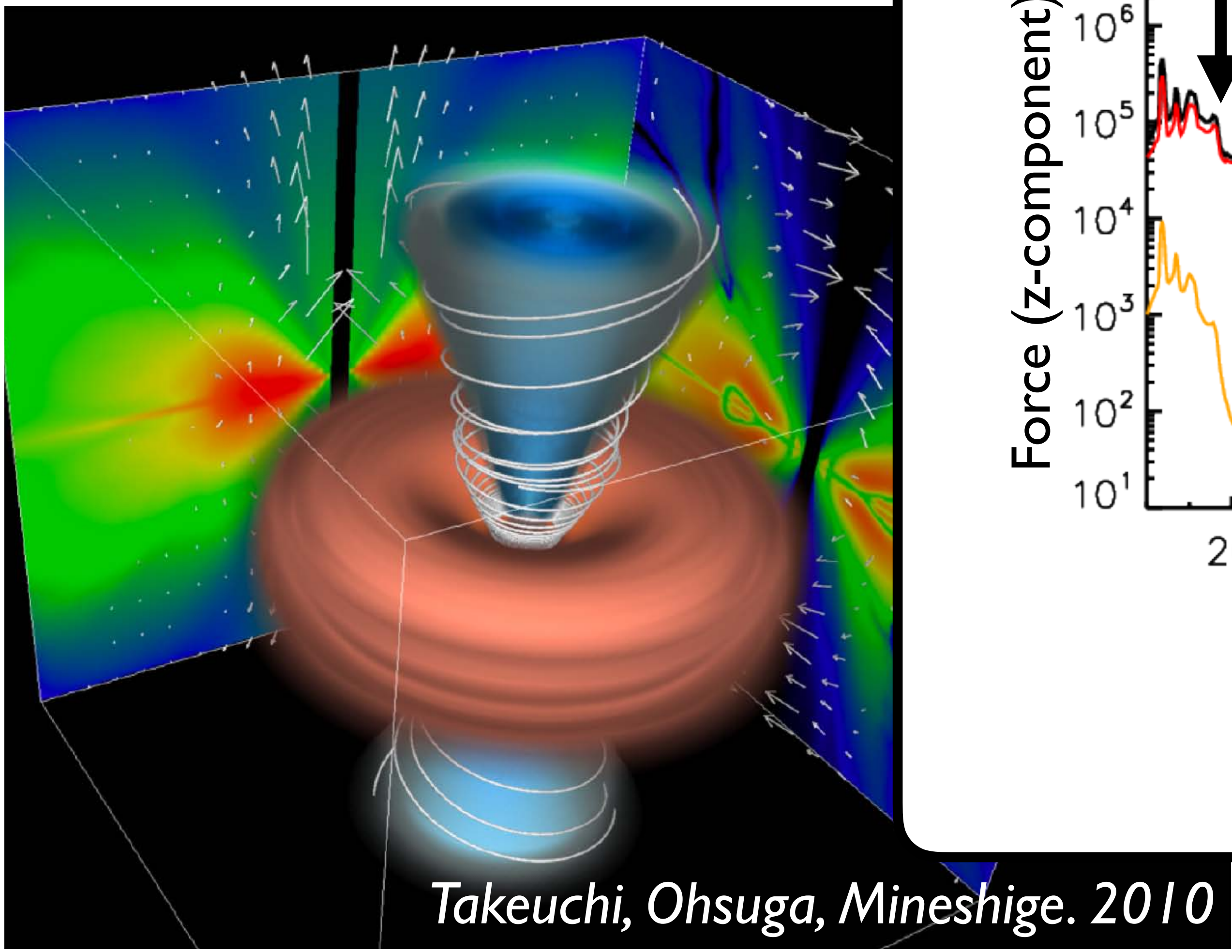
Mass density



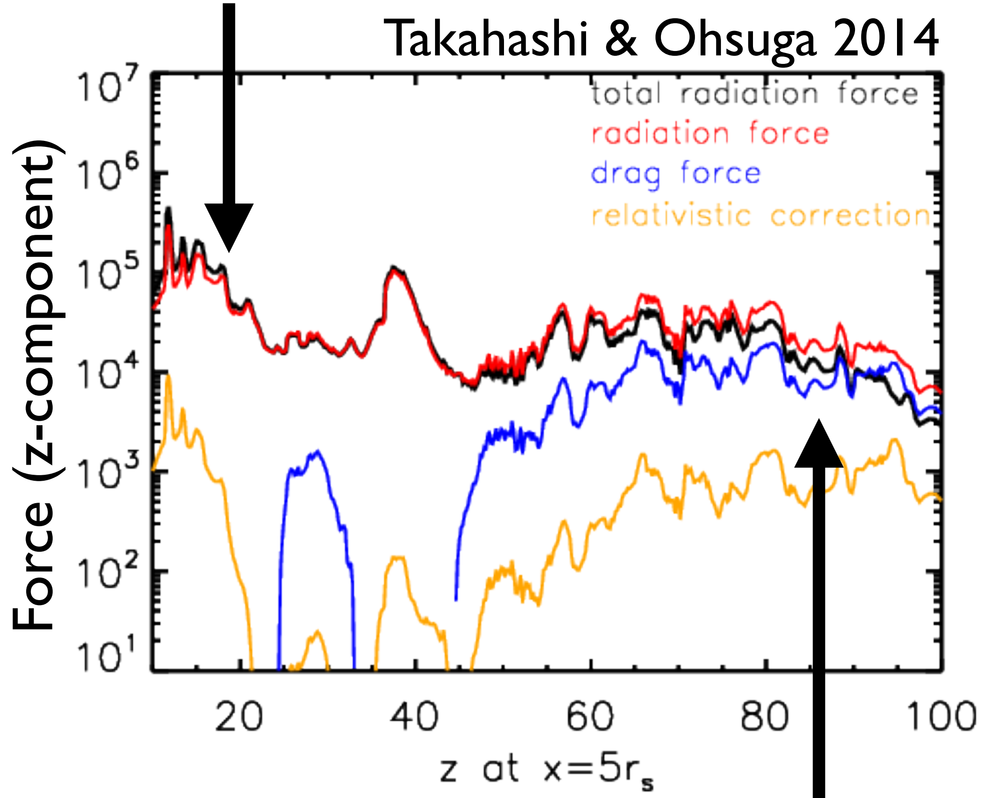
Strong radiation pressure supports the thick disk and generates the jets.

Photons mainly escape through the region around the rotation axis, so that the radiation pressure cannot prevent the accreting motion.

Radiatively Driven Jet

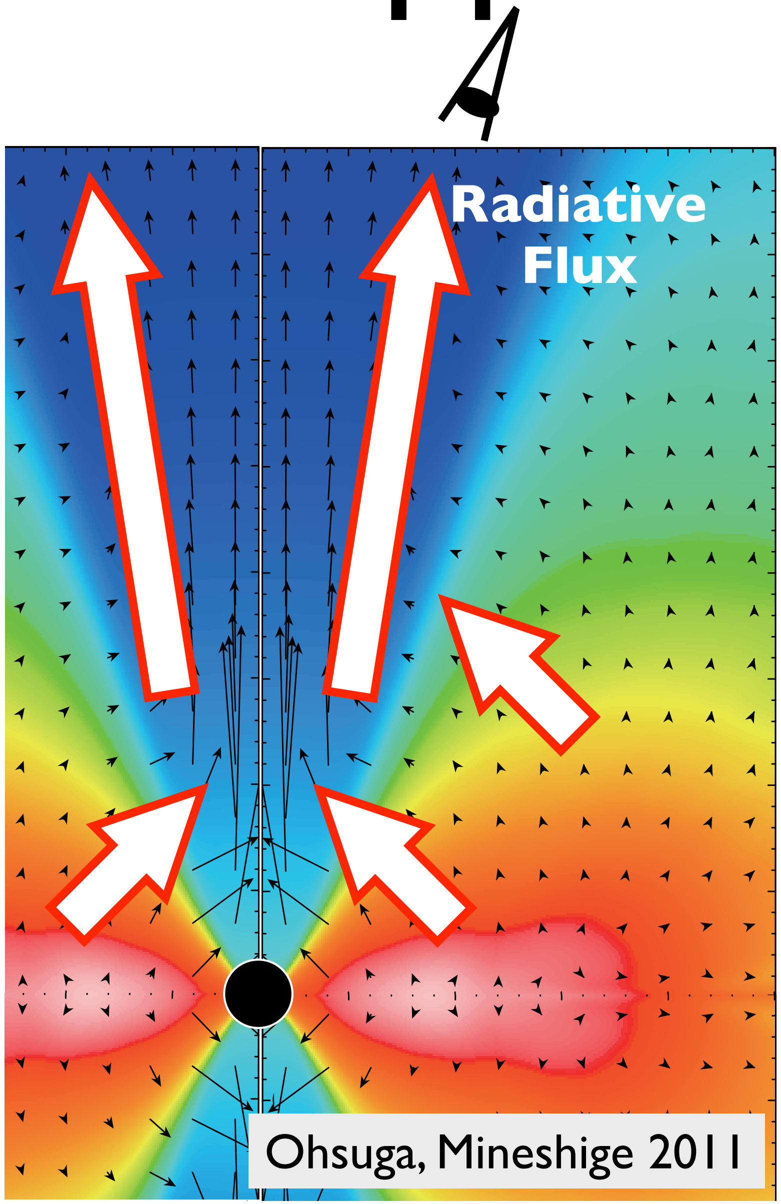


Acceleration via Radiation Flux Force



No acceleration because of
Flux Force ~ Drag Force

Apparent Luminosity



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

Thus observed luminosity is very sensitive to the observer's viewing angle.

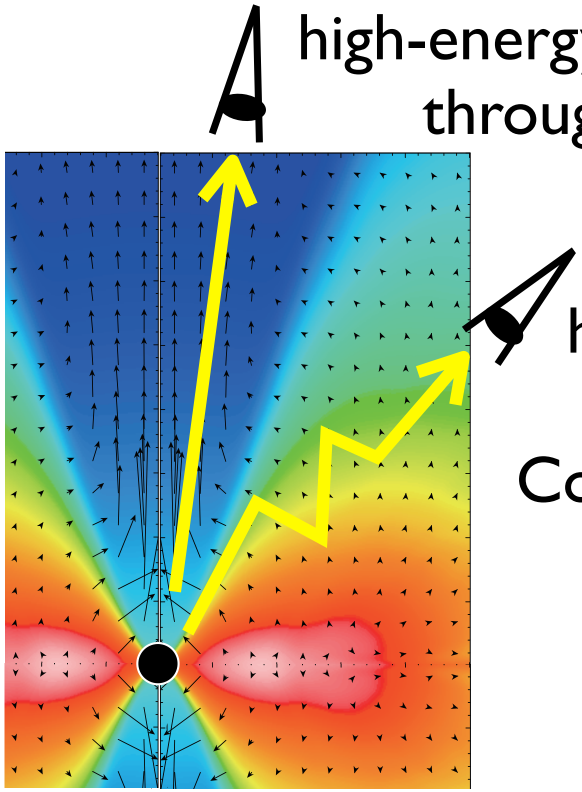
The apparent luminosity becomes highly super-Eddington for the face-on observers (**$22L_{Edd}$** for $\lesssim 20°$ in the case of Mdot$\sim 100L_{Edd}/c^2$, $L_{disk}\sim 3L_{Edd}$).

Large luminosity of ULXs ($>10^{39\text{-}40}$erg/s) can be explained for the face-on case.

X-ray spectra

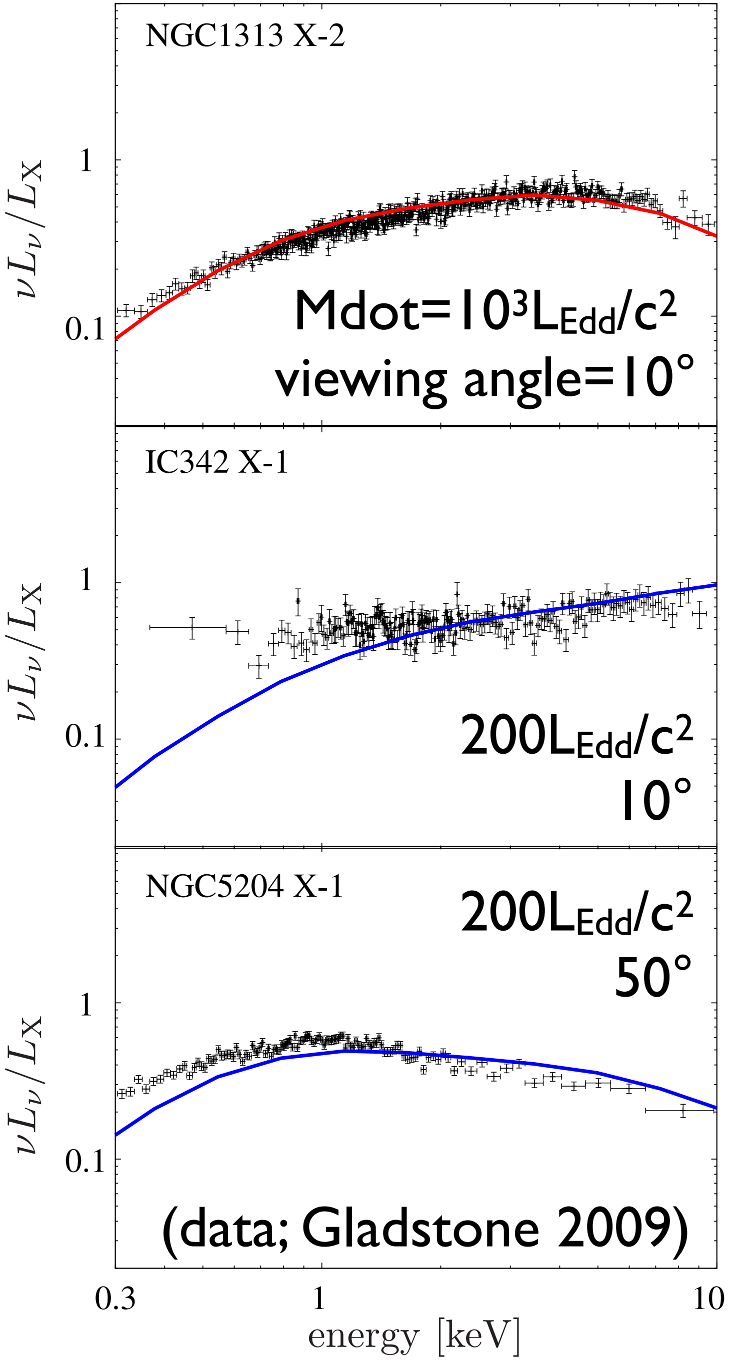
X-ray spectra, calculated by the post-processing radiation transfer, nicely fit the observations (ULXs).

hard X-ray is observed since high-energy photons escape through the funnel



hard X-ray is reduced by Compton down-scattering

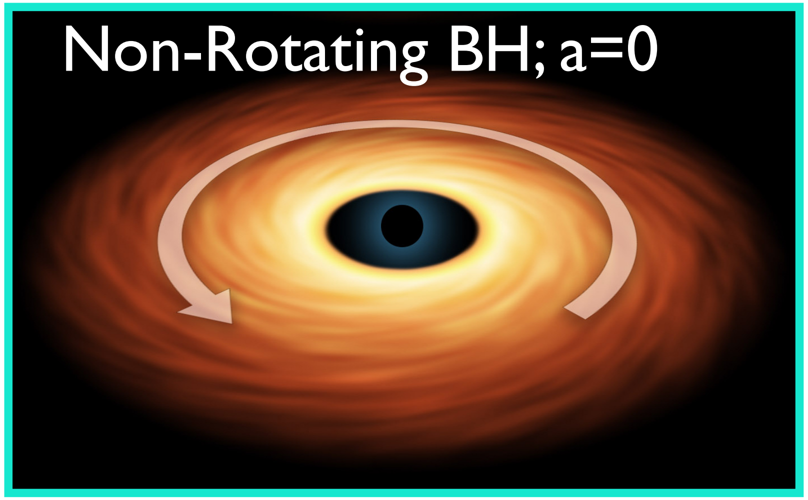
Kawashima et al. 2012

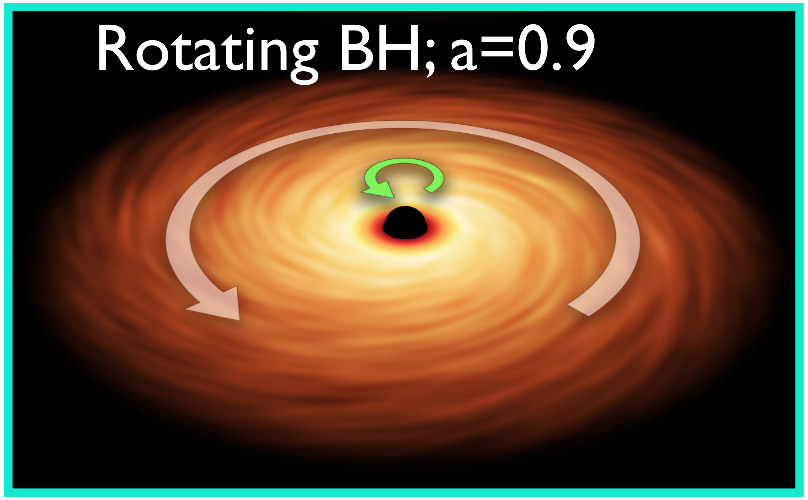


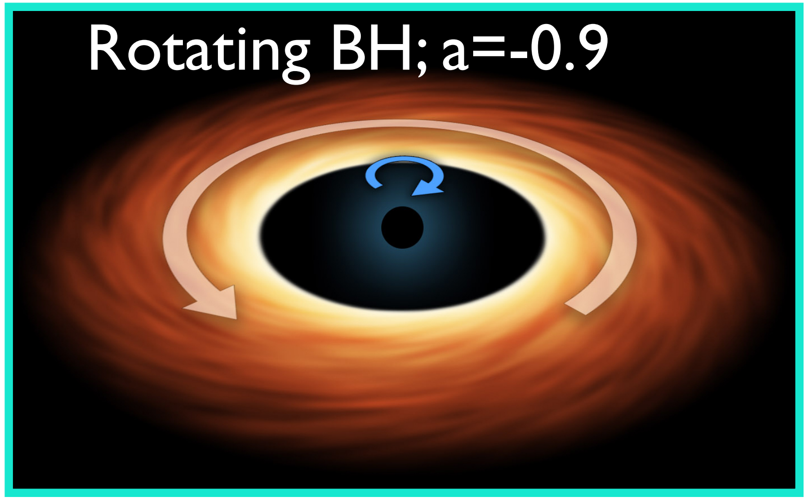
Effect of BH spin

Disk luminosity and jet power might depend on the BH spin. We perform simulations of the super-Eddington flows around BHs with a=0.9, 0, -0.9.

*a: spin parameter

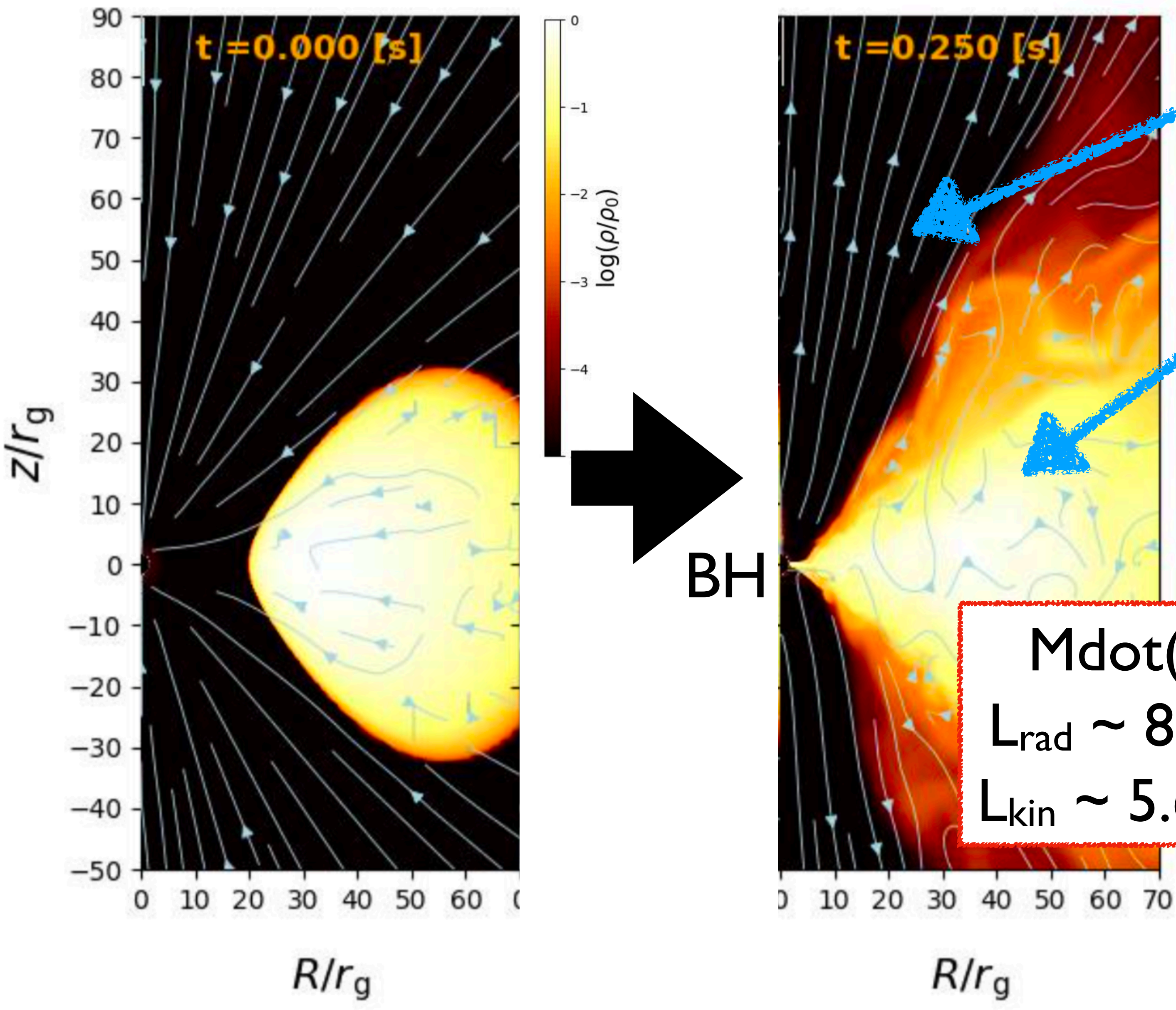






(c)NASA

Effect of BH spin



Radiatively-driven jet

Super-Edd. disk

BH (a*=0)

Mdot(BH) ~ 410L_{Edd}/c^2

L_{rad} ~ 8L_{Edd} → η_{rad} ~ 2.0%

L_{kin} ~ 5.6L_{Edd} → η_{kin} ~ 1.4%

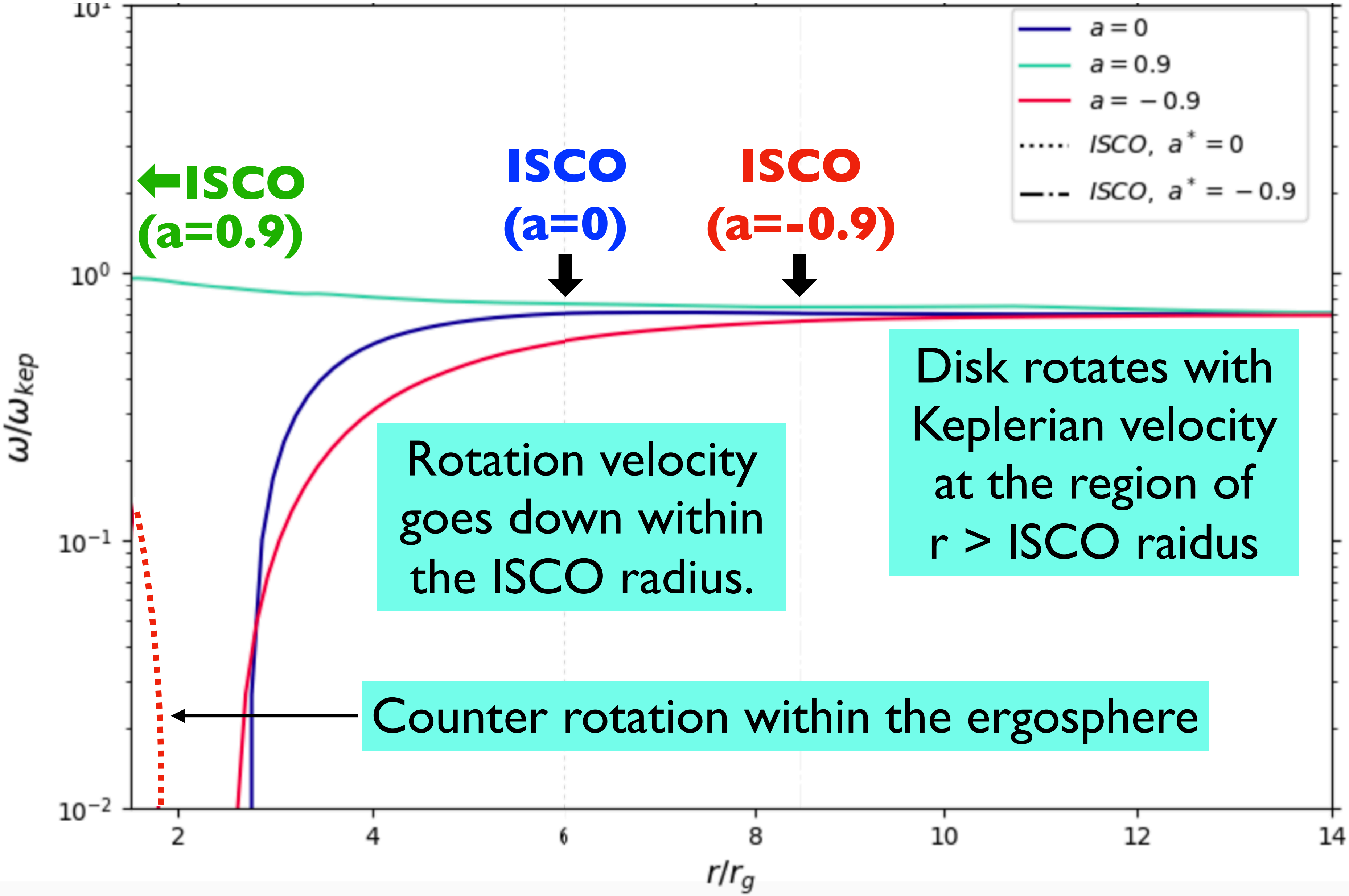
Preliminary

Utsumi et al. in prep.

Disk rotation

Preliminary

Utsumi et al. in prep.

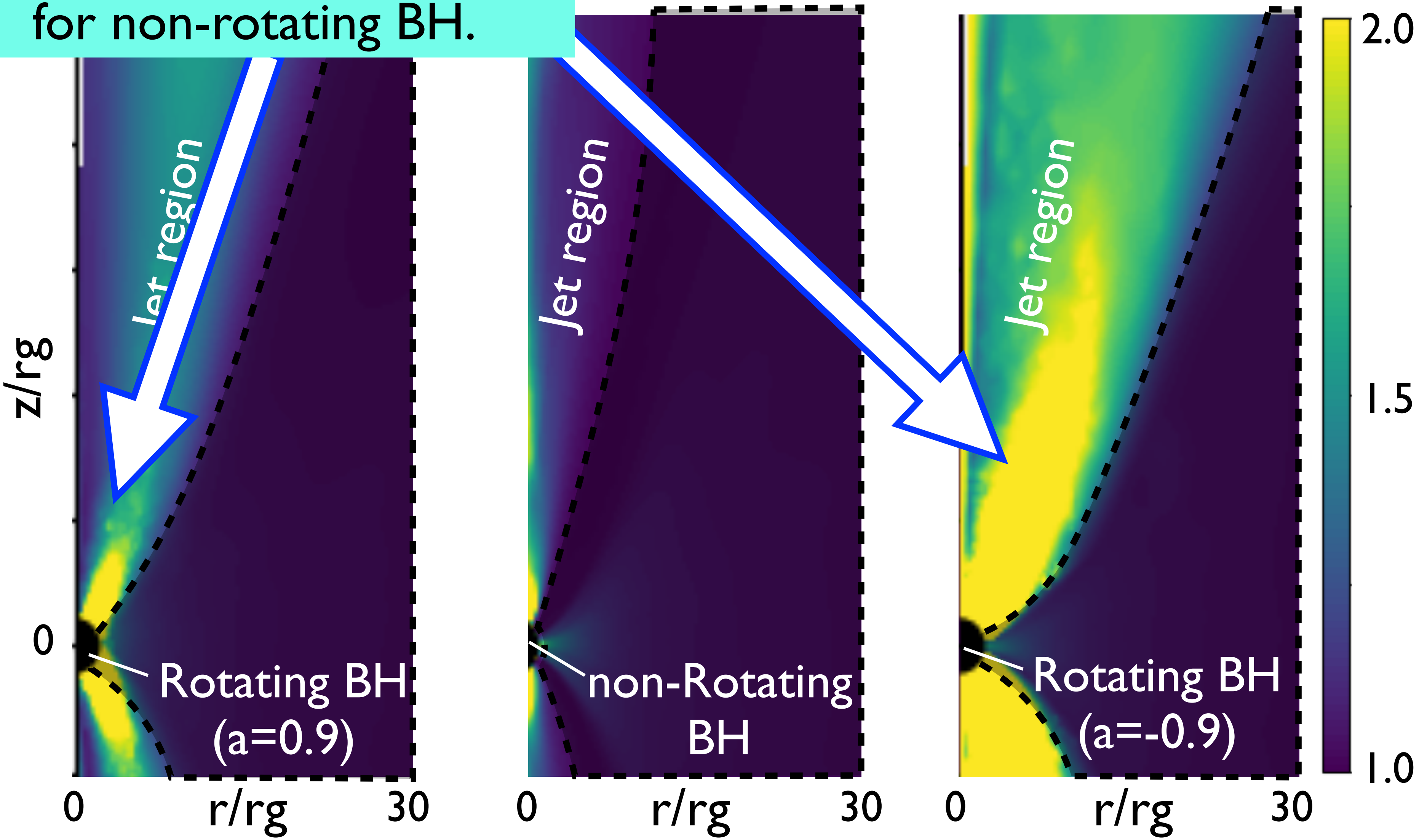


Lorentz factor

Preliminary

Utsumi et al. in prep.

Jet velocity (Lorentz factor) is larger for rotating BH than for non-rotating BH.



BH spin & Jets

Preliminary

Utsumi et al. in prep.

	L_{rad} vs L_{kin}	**Rad. Conversion Efficiency** $L_{rad}/(\mathrm{Mdot}\ c^2)$	**Jet Conversion Efficiency** $L_{kin}/(\mathrm{Mdot}\ c^2)$
a=0.9	$L_{rad} < L_{kin}$	**6%**	**11%**
a=0	$L_{rad} > L_{kin}$	**2%**	**1.4%**
a=-0.9	$L_{rad} < L_{kin}$	**3%**	**5%**

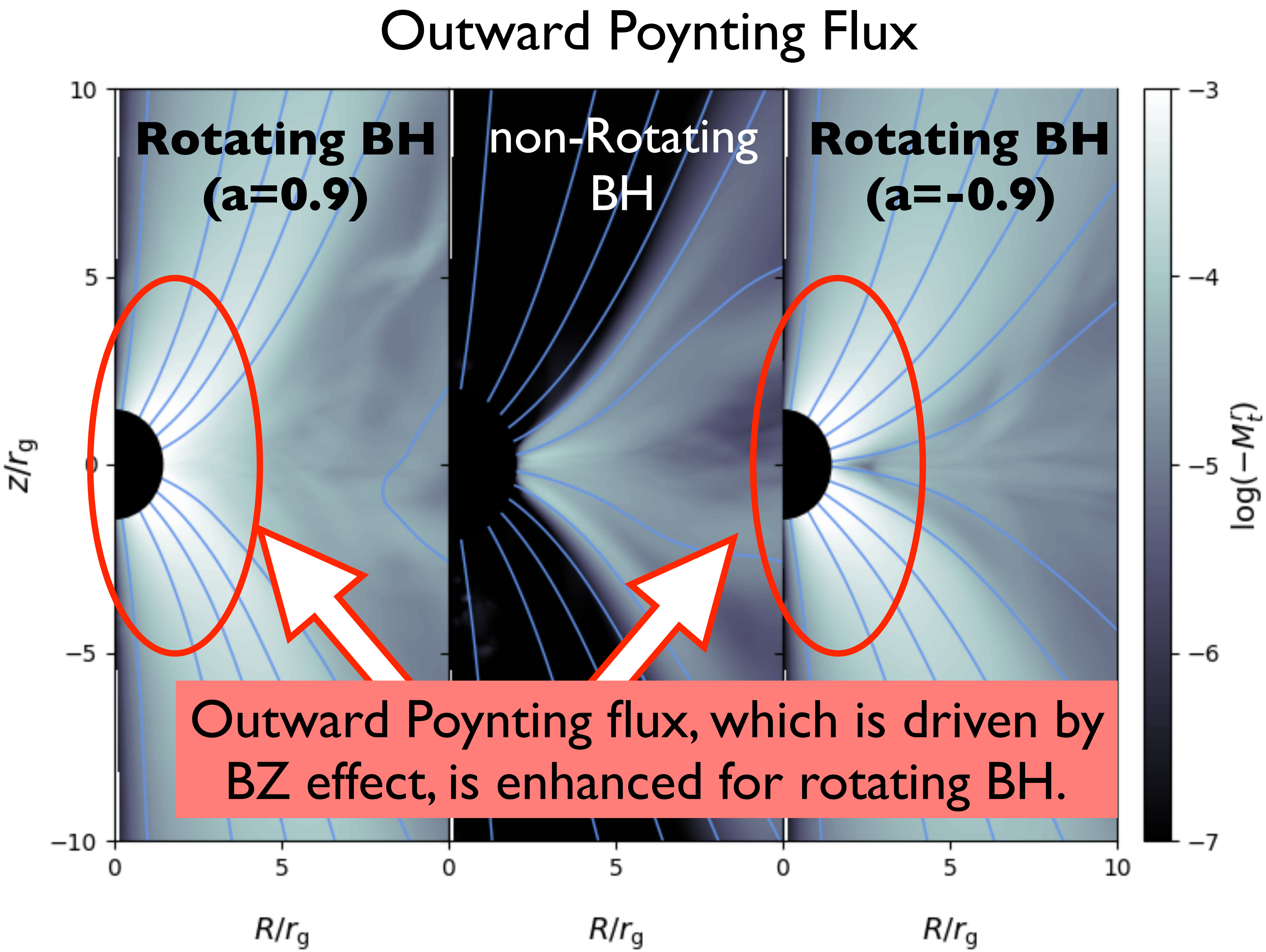
BH spin drives powerful jet ?

See Utsumi-kun's POSTER for details.

BH spin & Jets

Preliminary

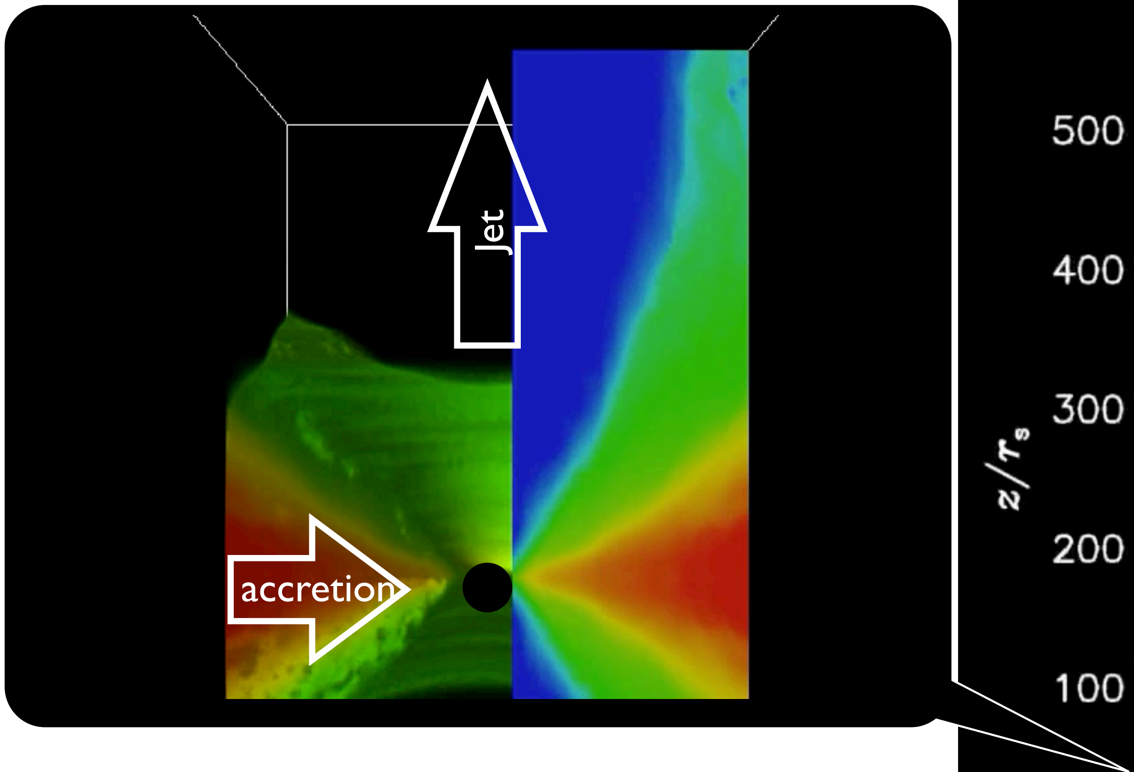
Utsumi et al. in prep.



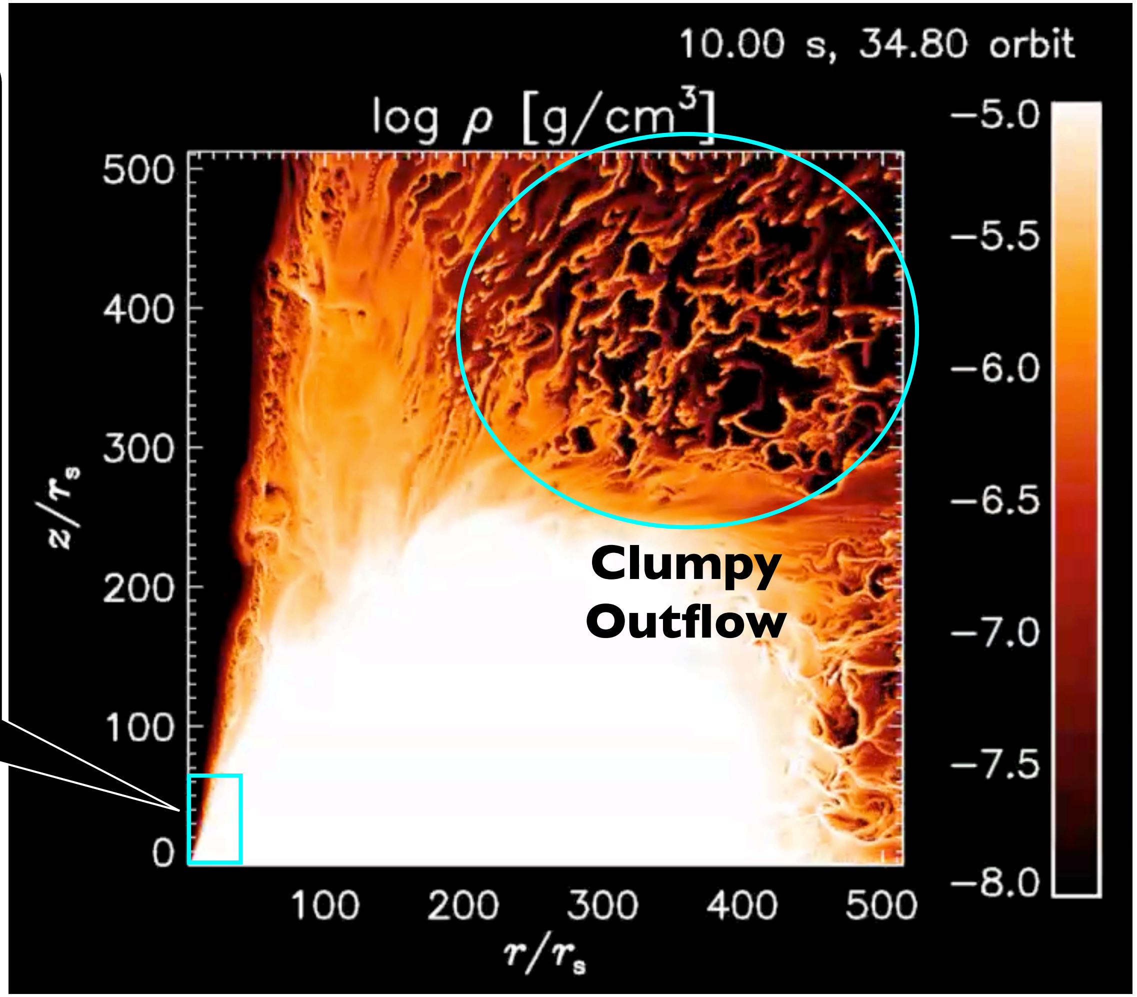
Outward Poynting flux, which is driven by BZ effect, is enhanced for rotating BH.

Wind Outflows from Super-Edd. Disks

Super-Eddington disk+ Jet

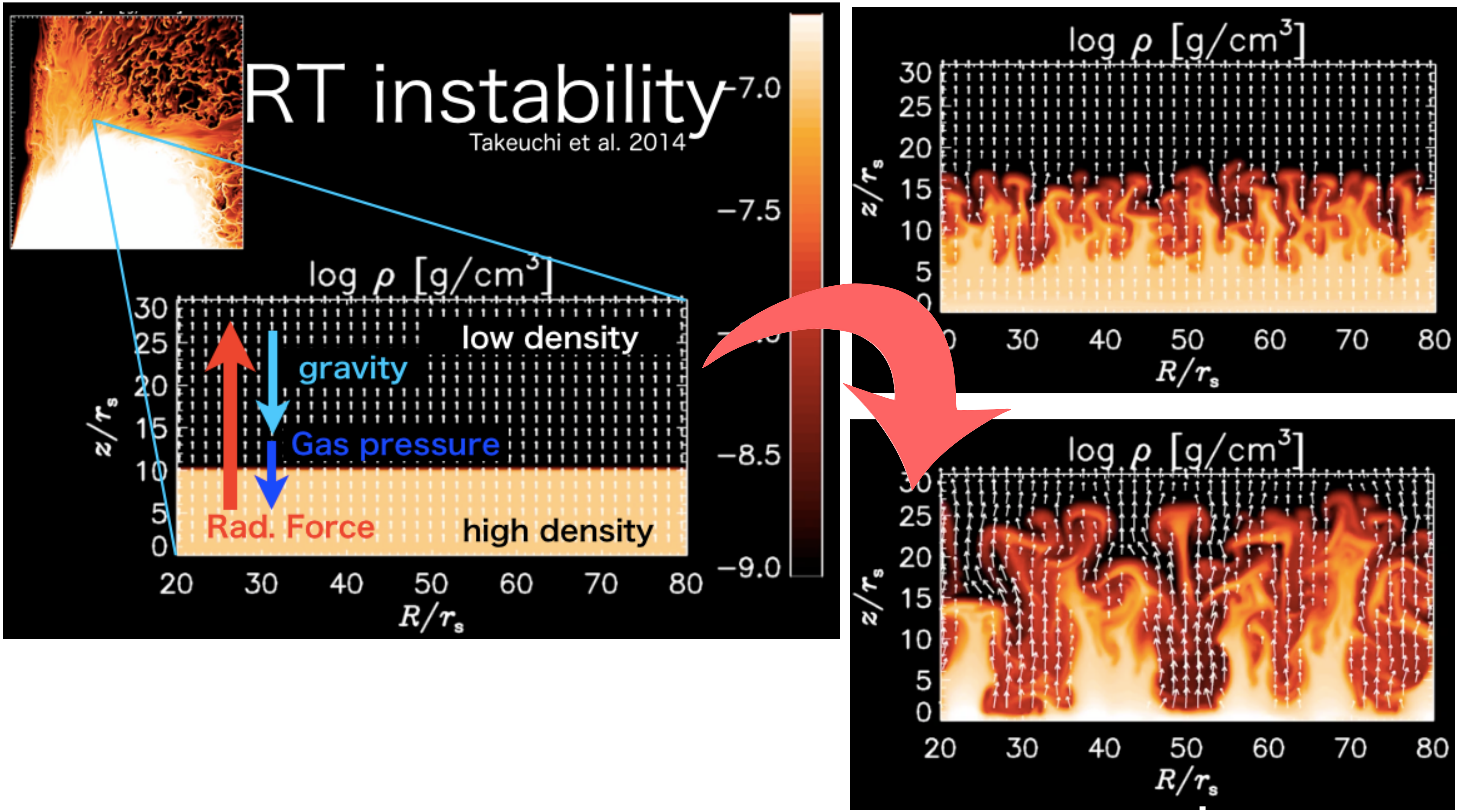


Takeuchi, Ohsuga, Mineshige 2013

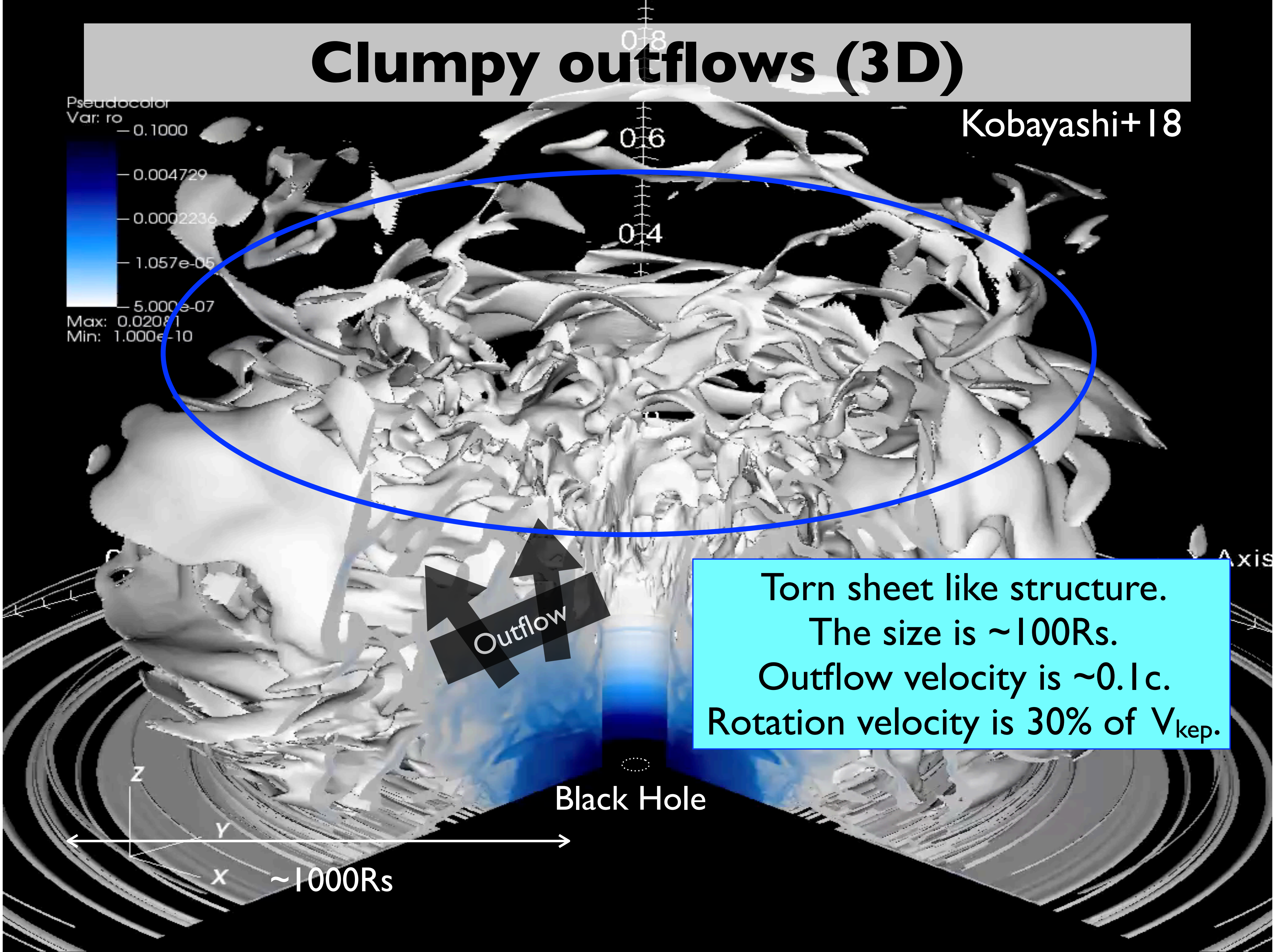


Time-dependent, Clumpy outflow with wide angle

RT instability



Clumpy outflows (3D)



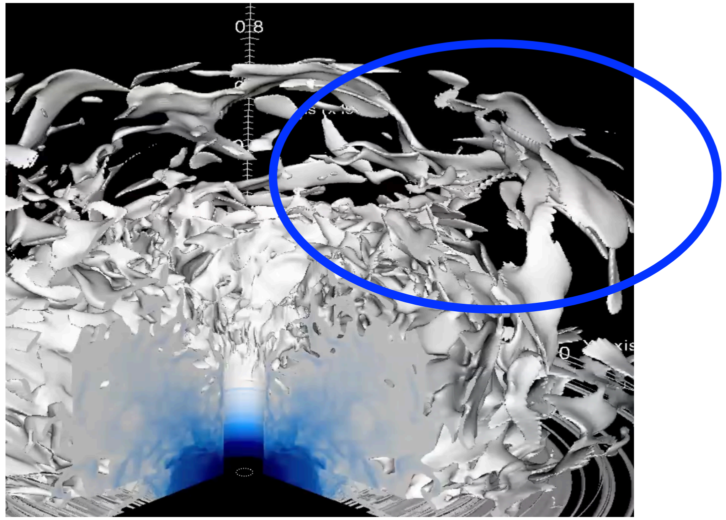
Torn sheet like structure.
The size is ~100Rs.
Outflow velocity is ~0.1c.
Rotation velocity is 30% of V_{kep}.

Sheet like structure

Outflow velocity ~ 0.1-0.2c

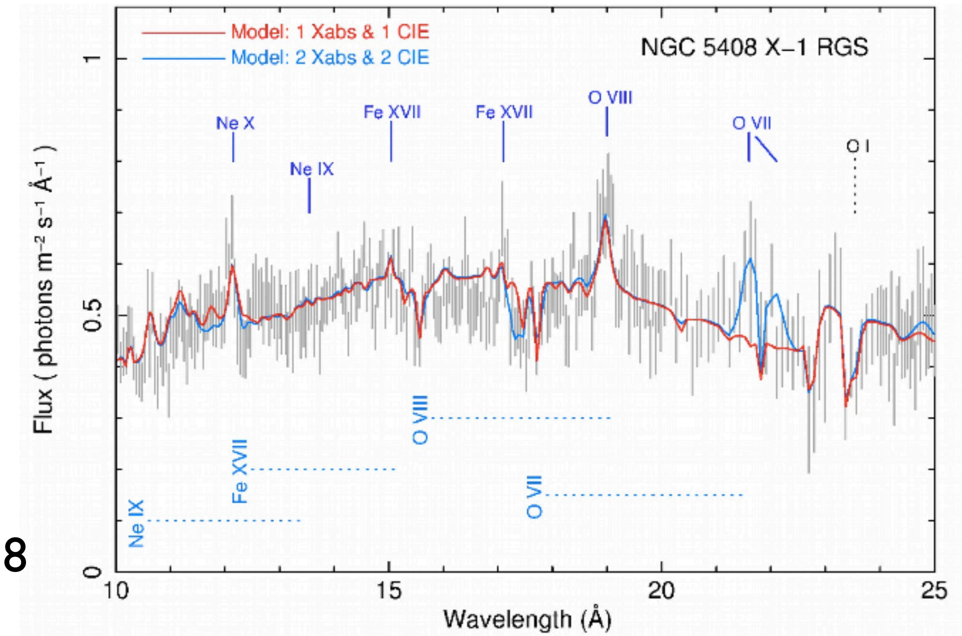
Size (azimuthal direction) ~ 100Rs

Rotation velocity ~ 30% of V_{kep}



Absorption lines

Outflow velocity of ~0.1-0.2c agrees with the observations of blueshifted absorption lines.



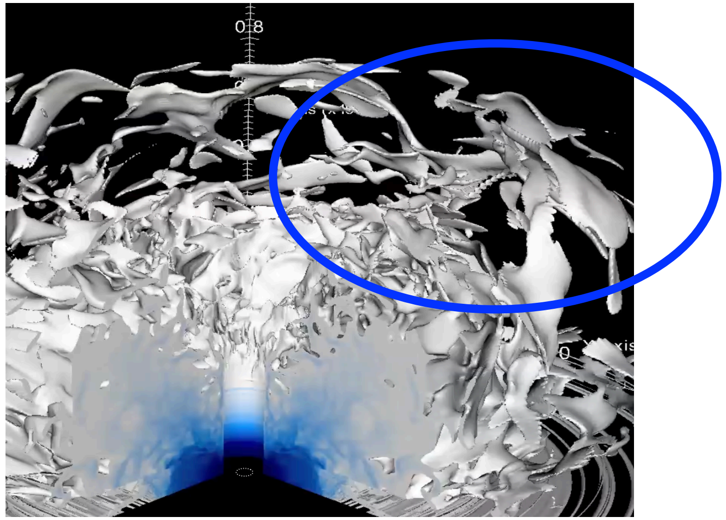
Pinto+16,
see also Kosec+18

Sheet like structure

Outflow velocity ~ 0.1-0.2c

Size (azimuthal direction) ~ 100Rs

Rotation velocity ~ 30% of V_{kep}



Time variation

Timescale of the luminosity variation (100Rs/0.3V_{kep}) is

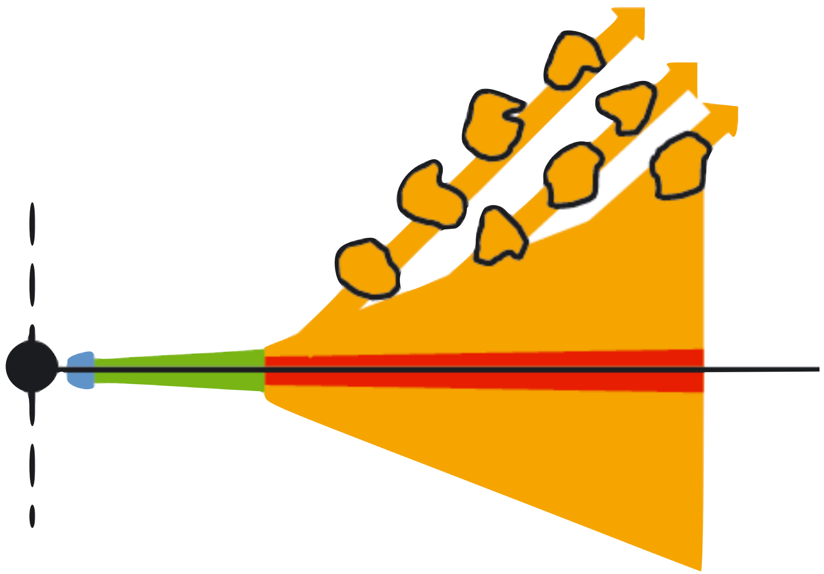
$$\sim 2.5 \left(\frac{M_{\rm BH}}{10\ M_\odot}\right)\left(\frac{\ell^{\theta}_{\rm cl}}{10^2\ r_{\rm S}}\right)\left(\frac{r}{10^3\ r_{\rm S}}\right) \mathrm{s}$$

Our result is consistent with the observations of ULXs (Middleton+11) and V404 Cyg (Motta+17) in the case of M_{BH}~10-100Msun.

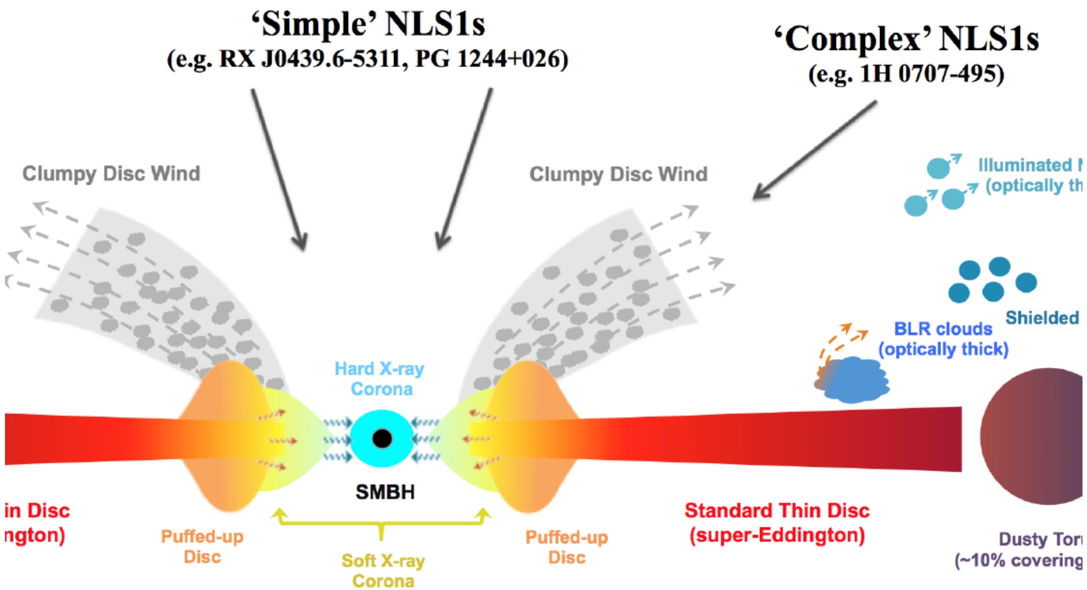
Clumpy outflows

Some ULXs exhibit the time variations of X-ray luminosity, implying the launching of clumpy outflows.

Launching of clumpy winds is also reported by observations of NLS1s or V404 Cyg.



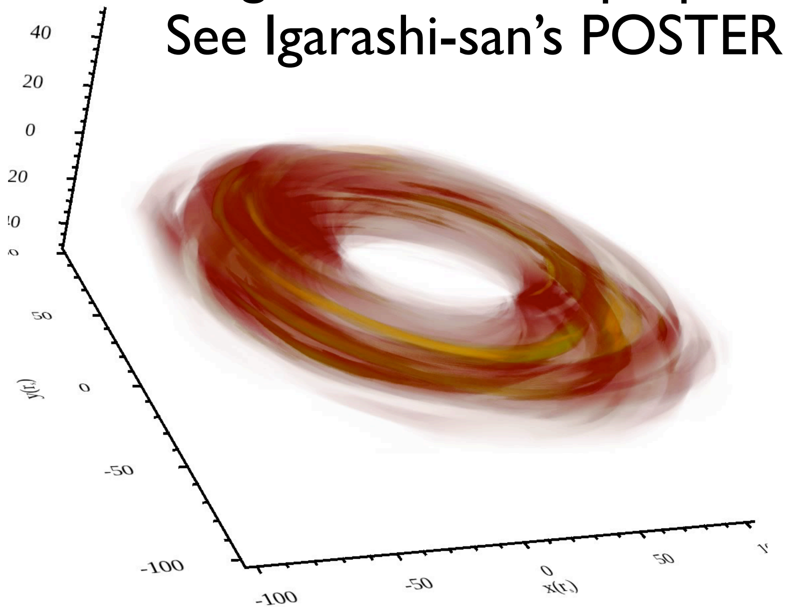
Middleton+11



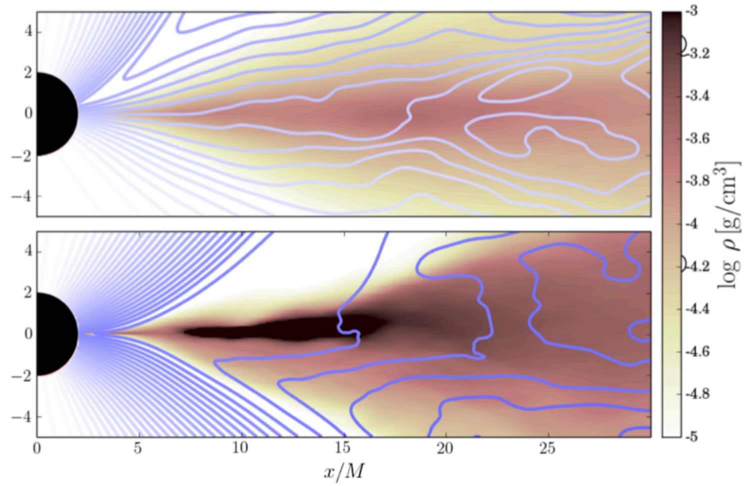
Jin+17 see also Motta+17

Simulations of near-Edd. disk

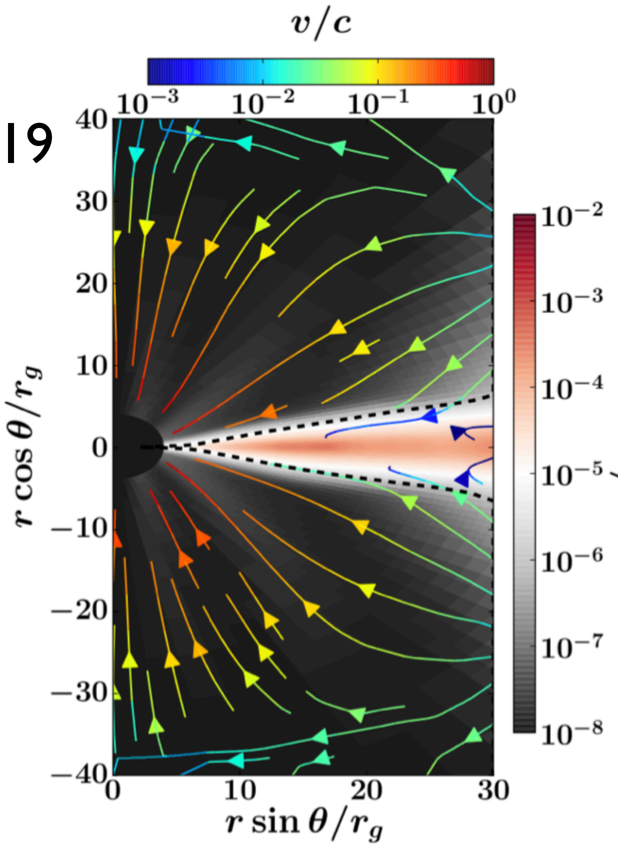
Igarashi et al. in prep.
See Igarashi-san's POSTER



Sadowsiki et al. 2016

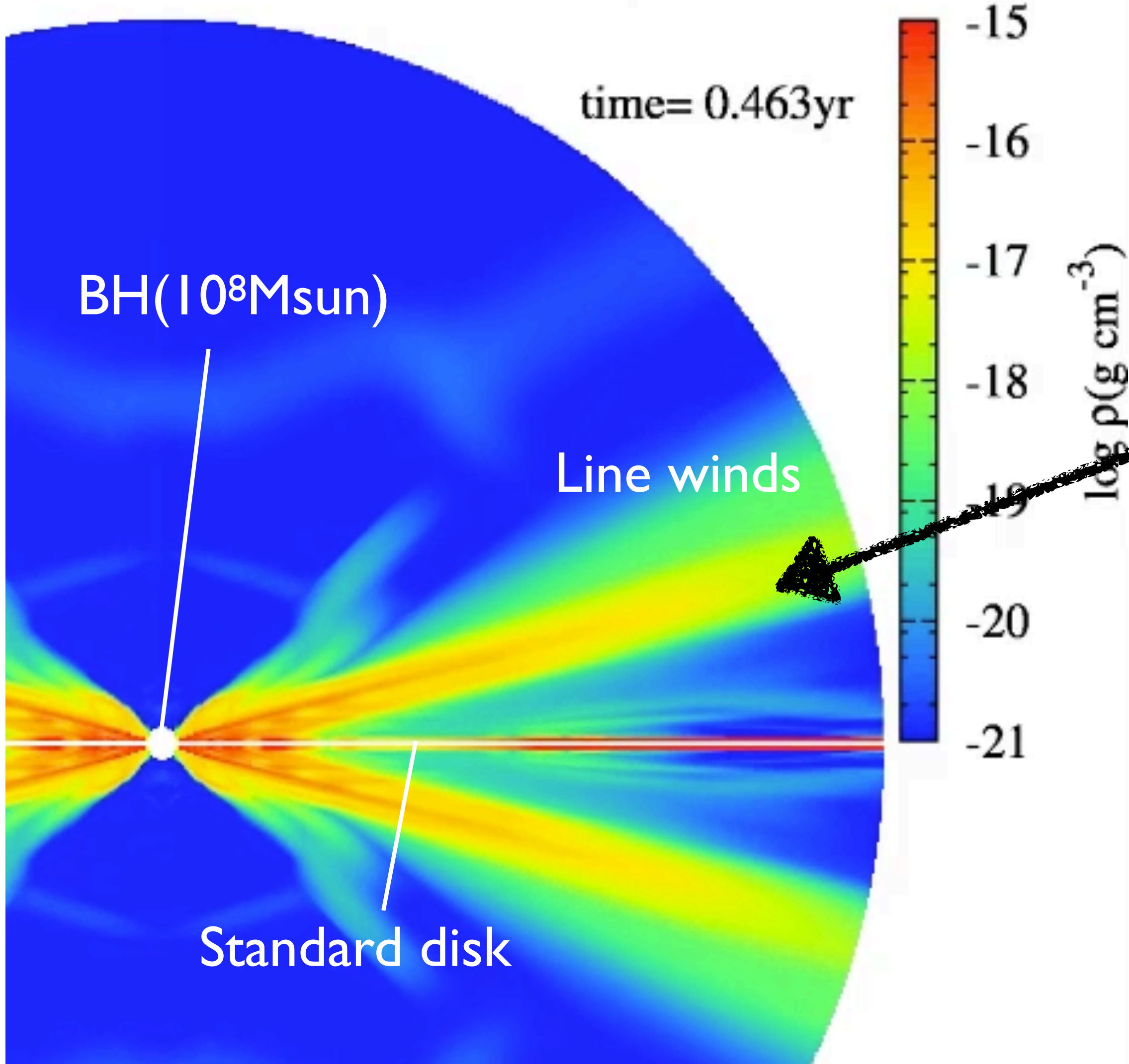


Jiang et al. 2019



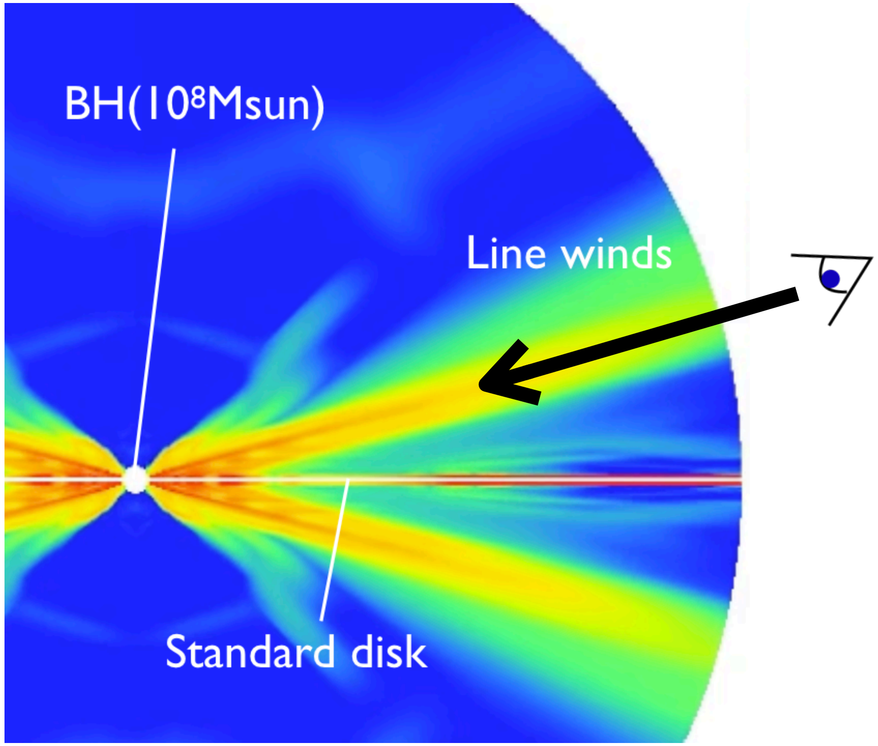
Simulations of line-winds

Nomura et al. 2016
(see also Proga et al. 00, 04)

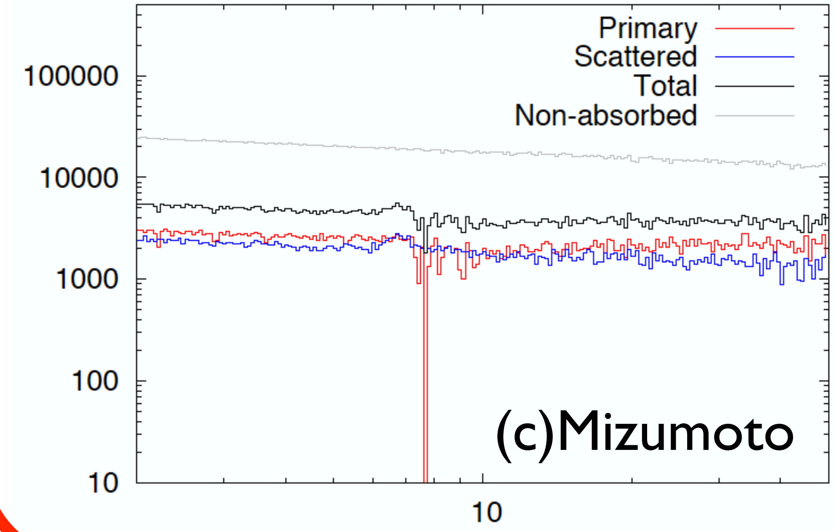


Funnel-shaped disk winds (~0.1c) are ejected at the region of 100Rg.

Spectra (line)

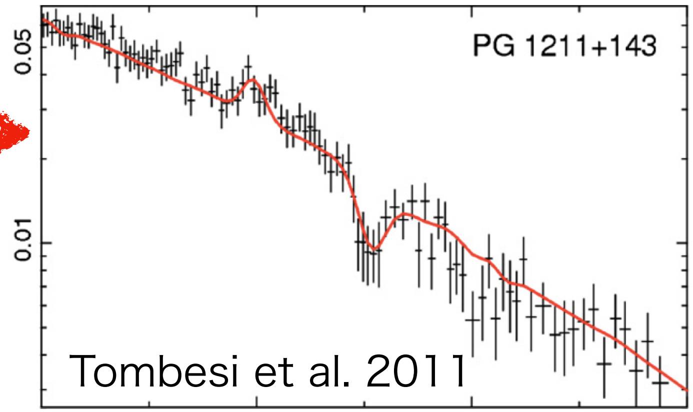


Simulated absorption line
by MONACO code



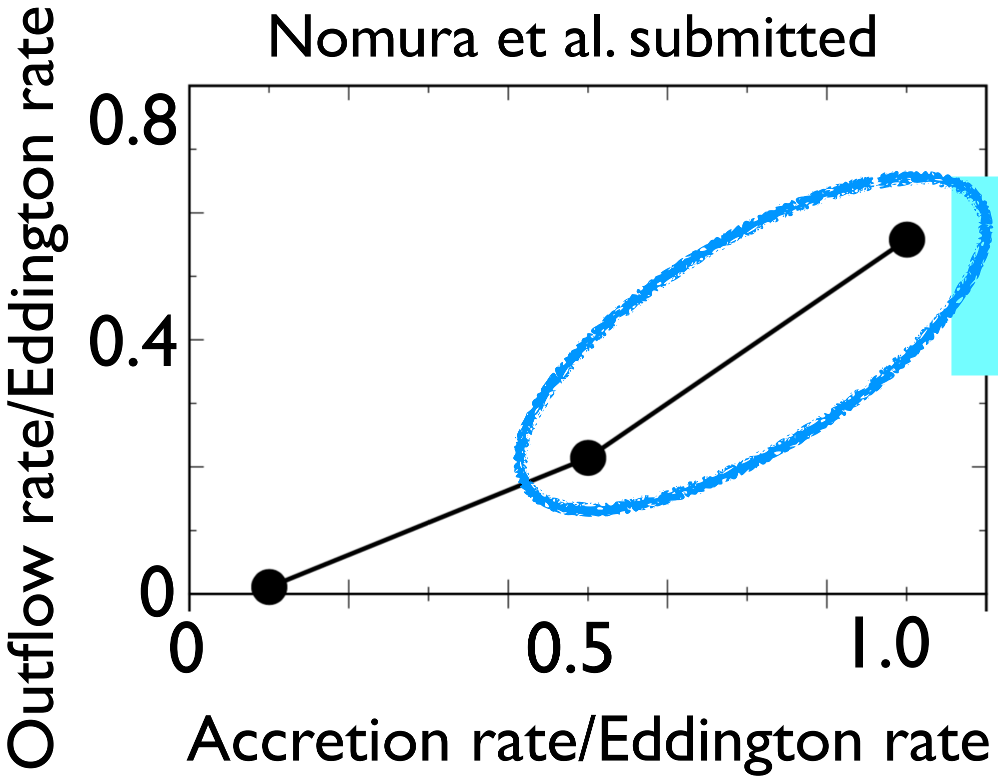
consistent

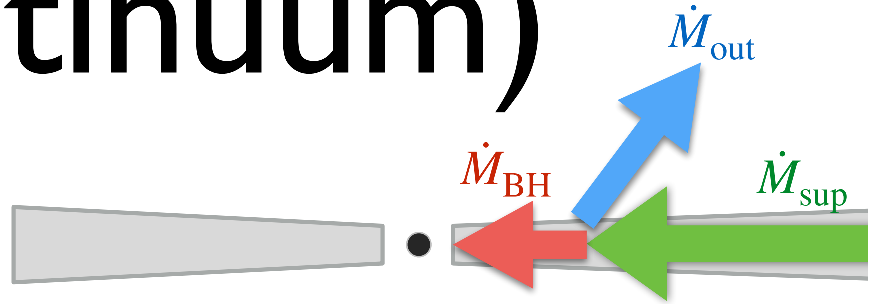
Observed line feature



Line-winds would be origin of UFOs, which is detected in some of Sy galaxies.

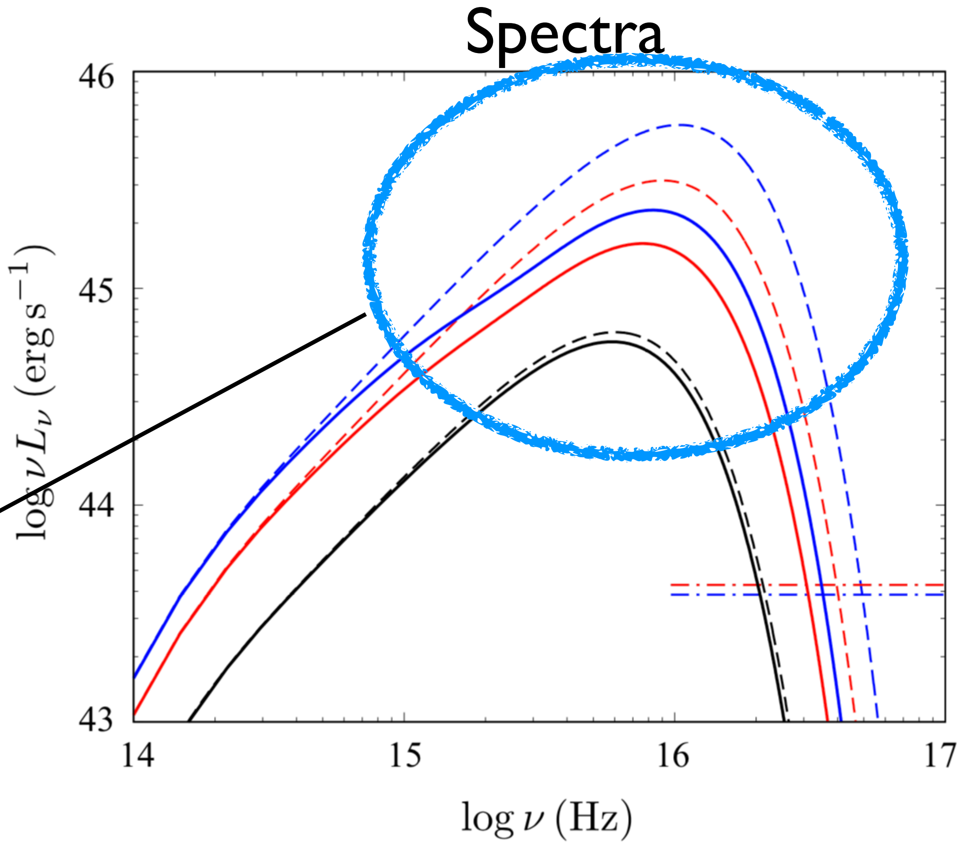
Spectra (Continuum)





Accretion rate is reduced by about half.

High-energy parts are reduced by the reduction of the accretion rate.



Summary

super-Eddington Flows

- Radiatively-driven jets are launched from the super-Eddington disks.
- Jet power (and disk luminosity) is enhanced by the BH spin. Probably this is due to the BZ effect.
- Disk winds from the super-Edd. disks fragment into many gas clouds via the RT instability.

near-Eddington Flows

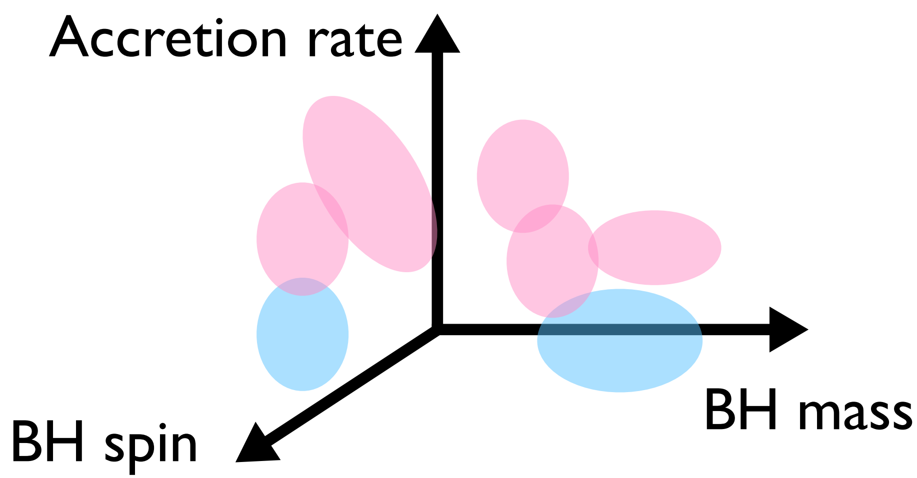
- Line-winds ejected from the disks would be origin of UFOs.
- Simulations of Jets from the near-Eddington disk are left as future works.

Important Keyword "3"

We need <u>three</u> steps in order to reveal BH.

Collaboration between observations and theory is important.

Theory/Model Hydrodynamics Simulations → **Radiation Transfer Calc.** ↔ **Observations**



We should understand BHs in <u>3D</u>-space (Mass, Accretion rate, Spin).