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Numerical simulations of super-Eddington accretion flows

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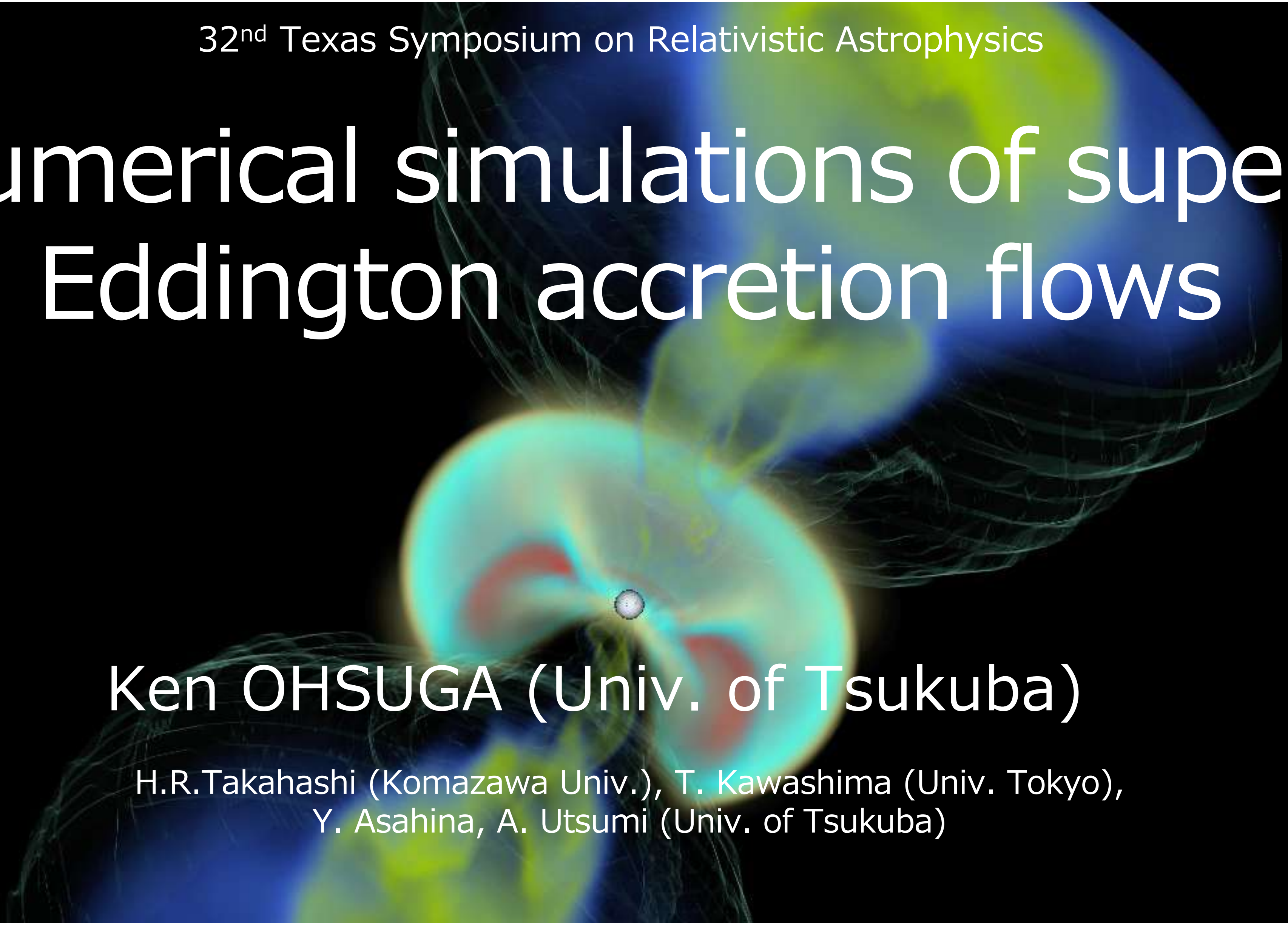
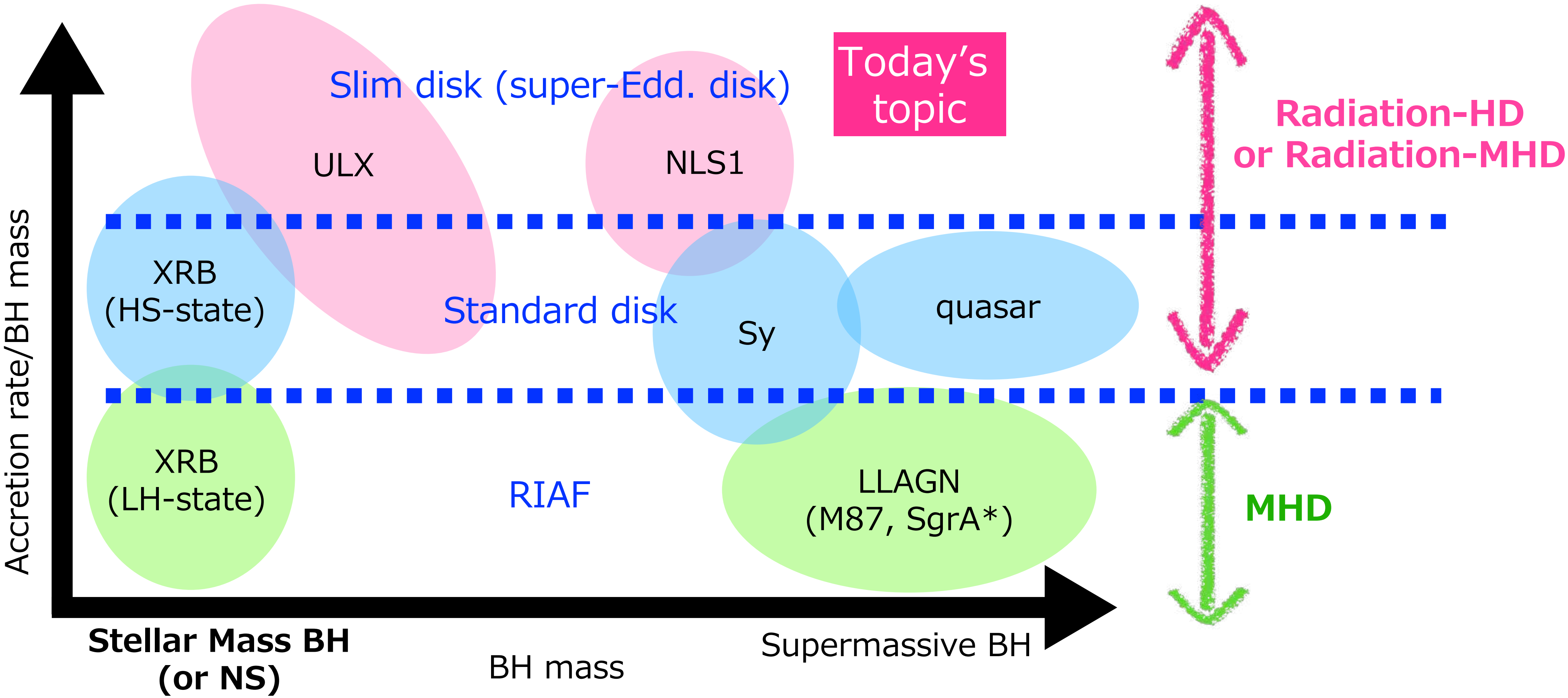


Three Accretion Modes



Development of research of Super-Edd. flows

1988~

1D approach Slim disk model has been established (Abramowicz et al. 1988)

Multi-dimensional Simulations

2005~

Radiation-HD sim. **Radiation-MHD sim.**

Quasi steady inflow-outflow structure has been revealed.

(**Ohsuga et al. 2005, 2009, Ohsuga & Mineshige 2011**, Jiang et al. 2014, 2019)

2014~

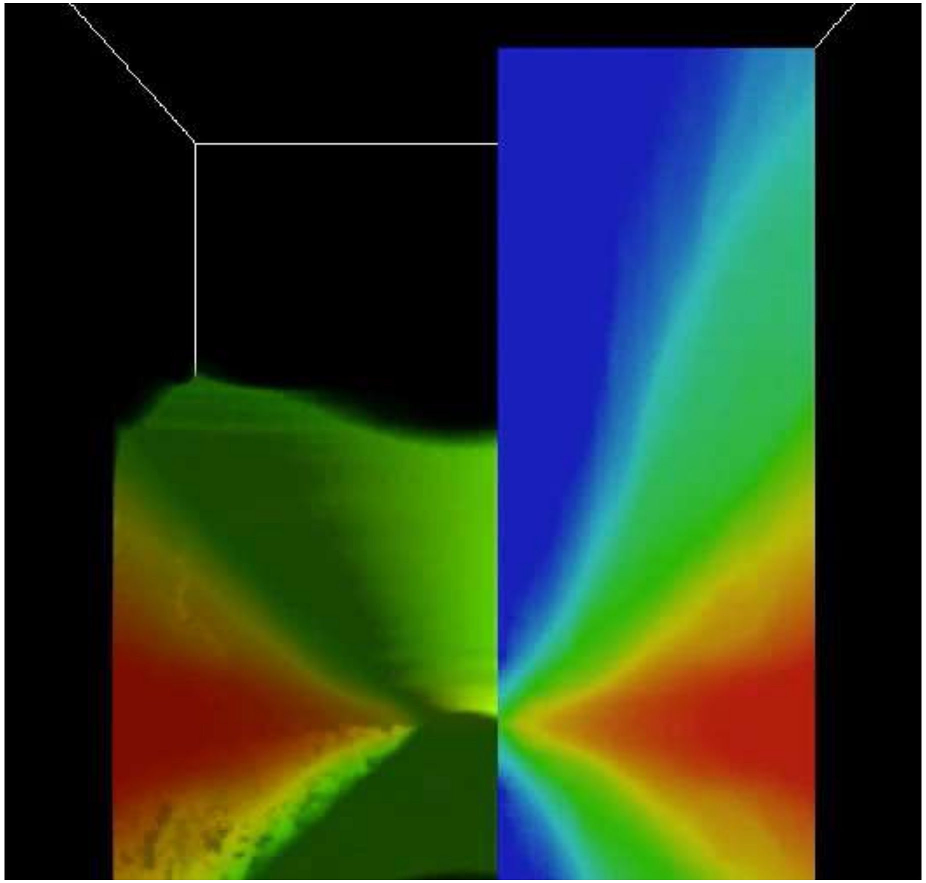
General Relativistic Radiation-MHD Sim.

General relativistic effects (e.g., BZ effect, LT precession) has been studied

(Sadowski et al. 2014, 1016, **Takahashi, Ohsuga et al. 2016, Utsumi, Ohsuga et al. 2022**, Brandon 2023, **Asahina & Ohsuga submitted**).

Radiation-HD/MHD simulations Super-Edd. Flows

Ohsuga et al. 2009



Setup

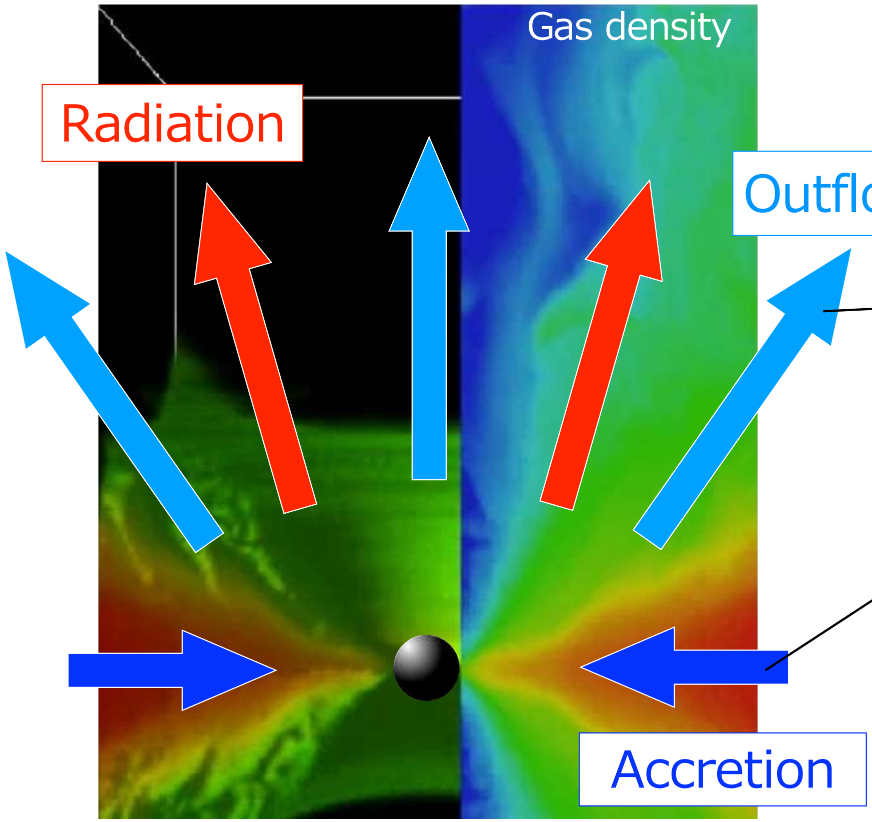
- BH mass: 10Msun
- Initial condition: equilibrium torus with embedded poloidal magnetic field (plasma-beta=100)

Quasi-steady structure

- The super-Eddington disks (Mdot ~ a few $100L_{Edd}/c^2$, Ldisk >> L_{Edd})
- Radiatively-driven outflows

see also Ohsuga et al. 2005; 2011, Ohsuga 2007, Jiang et al. 2014, 2019

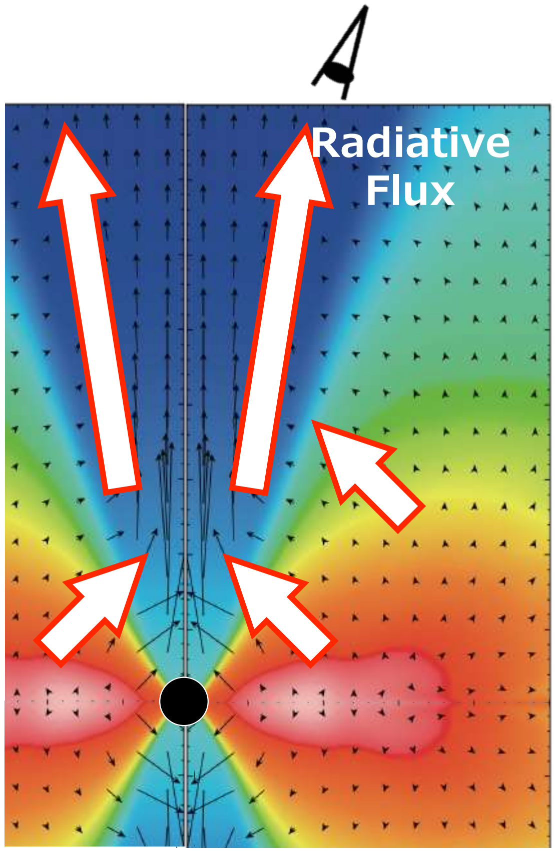
Why is super-Eddington accretion feasible?



<u>Radiatively driven outflows</u>:
Strong radiation pressure supports the thick disk and generates the outflows above the disk.

<u>Accretion</u>:
Photons mainly escape through the less-dense region above the disk. The radiation pressure cannot prevent the accreting motion within the disk.

Apparent Luminosity



Ohsuga, Mineshige 2011

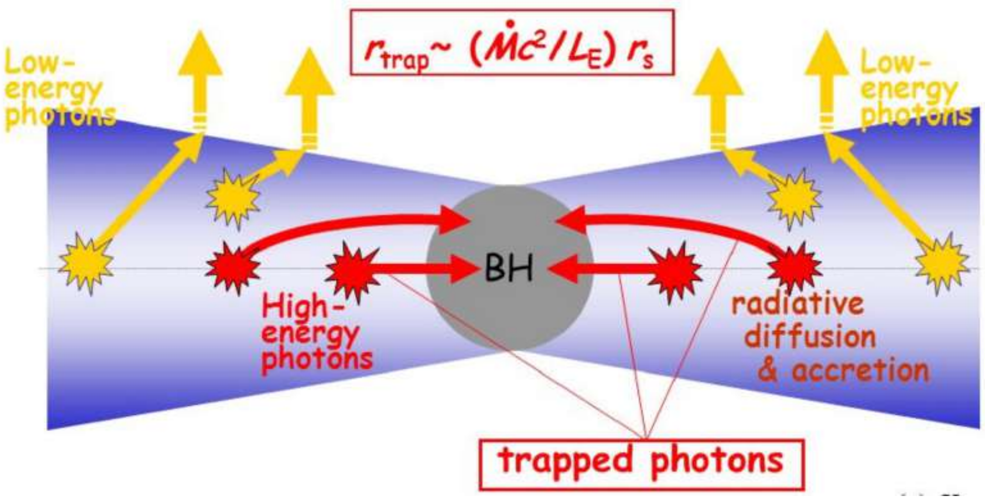
- The radiative flux is mildly collimated since the disk is optically and geometrically thick.
- Thus, observed luminosity is very sensitive to the observer's viewing angle.
- The apparent luminosity becomes highly super-Eddington for the face-on observers.

ex: $22L_{Edd}$ for $\lesssim 20°$
when $Mdot \sim 100L_{Edd}/c^2$ & $Ldisk \sim 3L_{Edd}$.

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

Photon trapping

Ohsug et al. 2002, 20023



Photon trapping:
Huge amount of radiation energy is swallowed by the black hole with accreting matter.

Radiation diffusion timescale

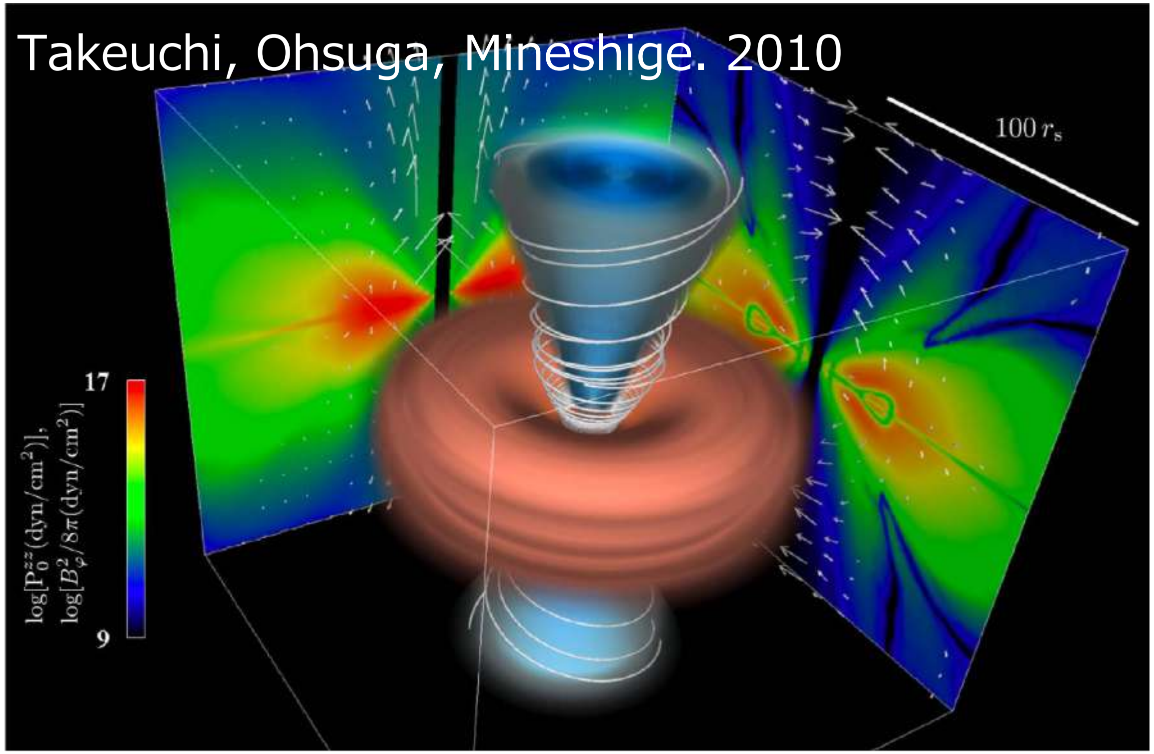
> Matter accretion timescale

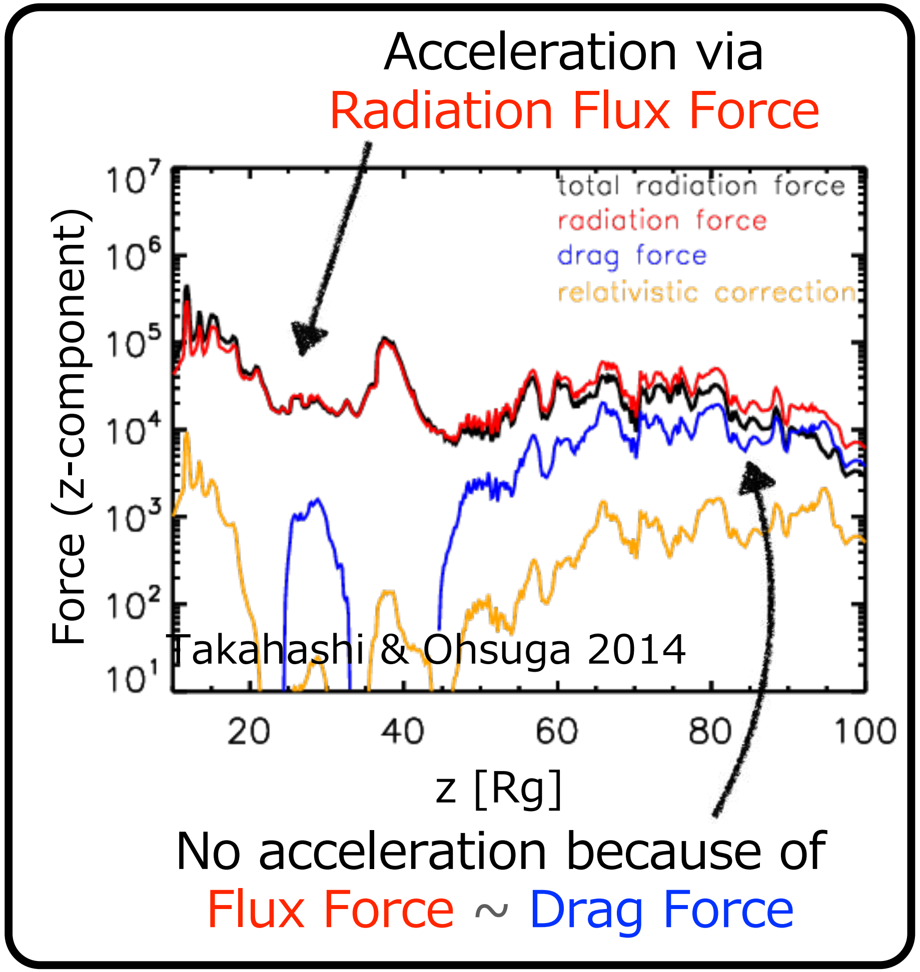
$$\rightarrow r_{trap} < \frac{\dot{M}c^2}{L_{Edd}} r_S$$

Photon-trapping occur
in super-Eddington accretion flows.

Radiatively-driven Jets

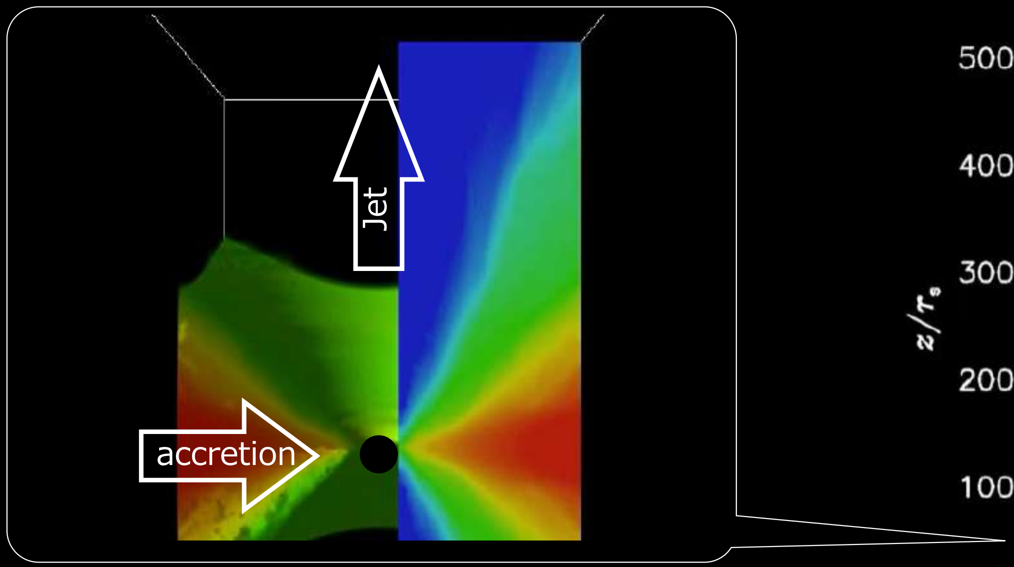
Resulting jet velocity (~0.3-0.5c) is roughly consistent with the jets in SS433.

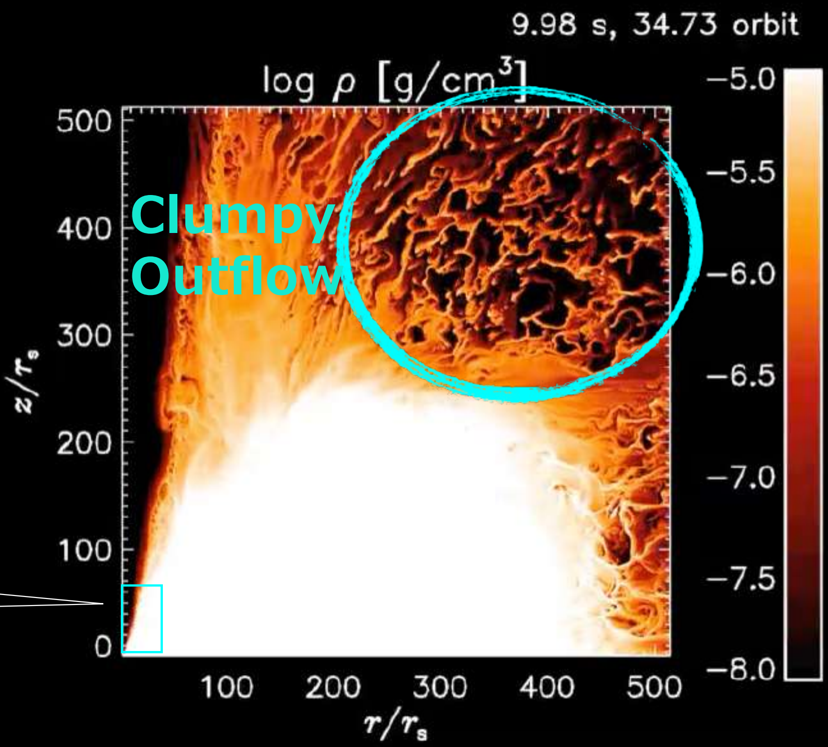




Clumpy Outflows

Takeuchi, Ohsuga, Mineshige 2013

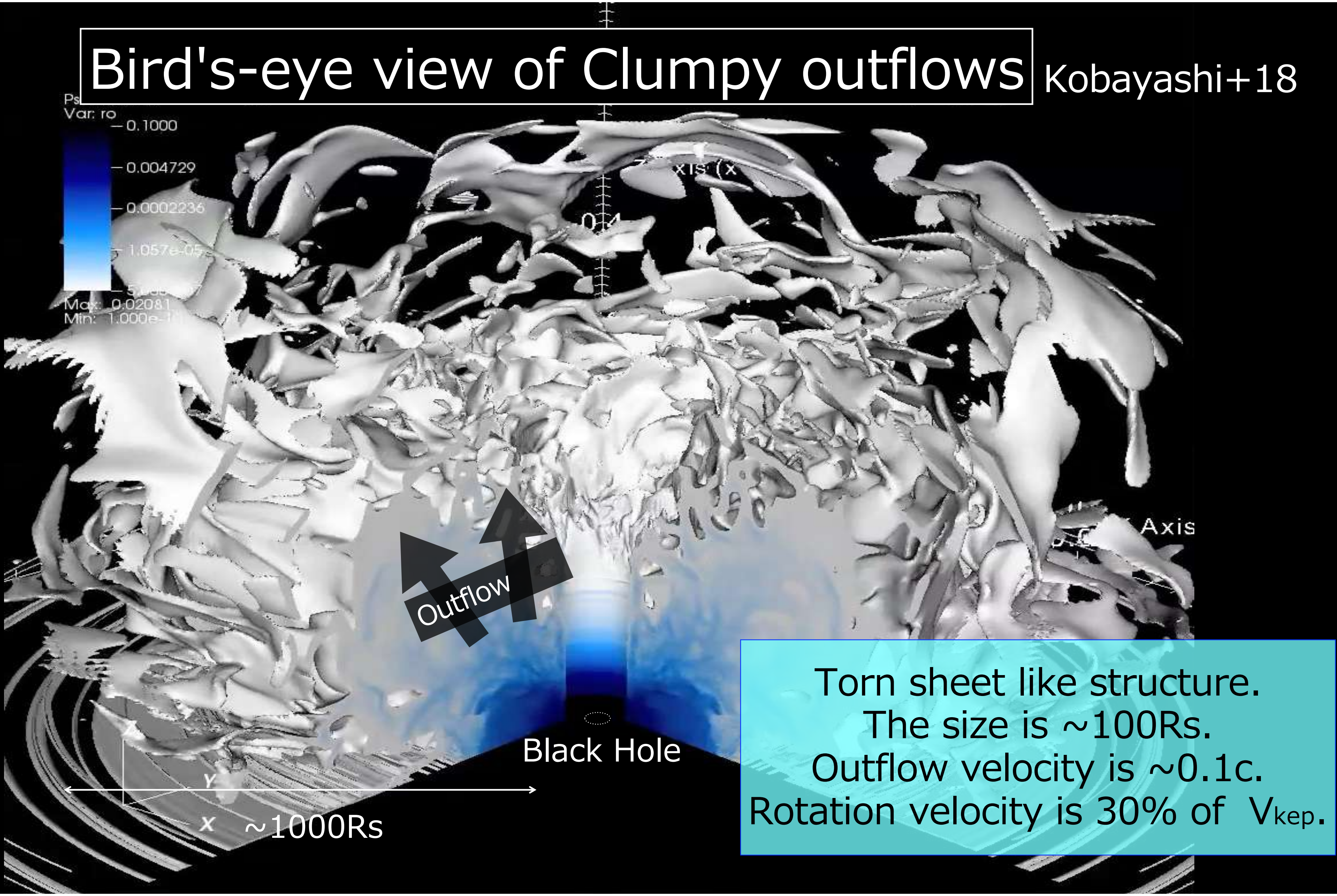




Clumpy outflows: Wind outflows fragment into many gas clouds

Bird's-eye view of Clumpy outflows

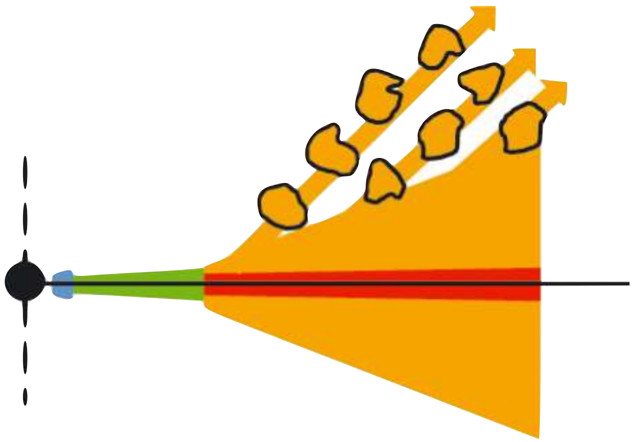
Kobayashi+18



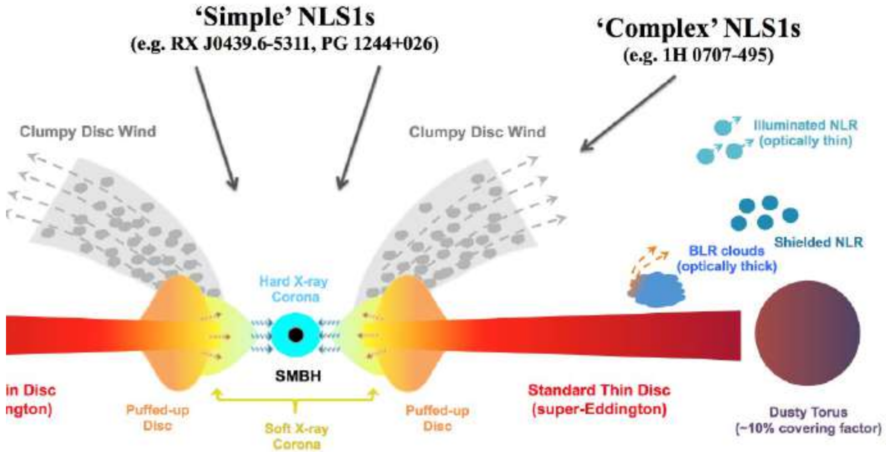
Observations of Clumpy outflows

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.

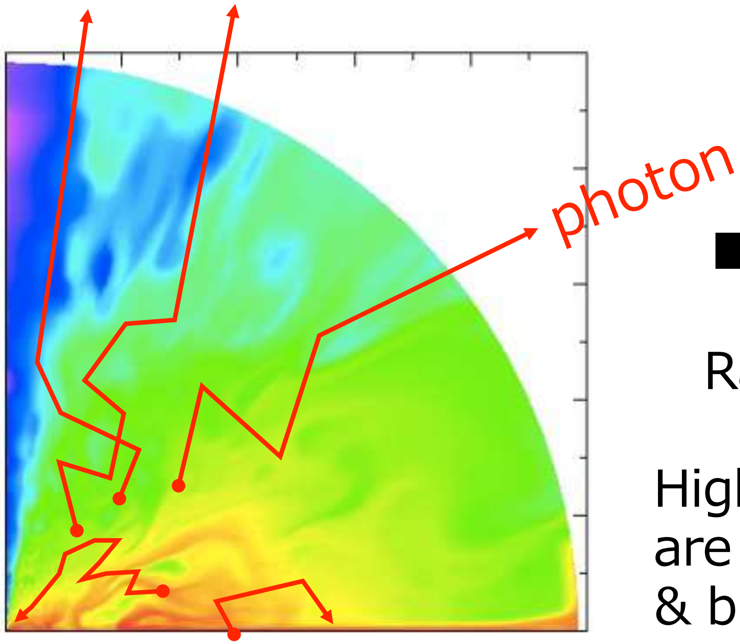


Middleton+11



Jin+17 see also Motta+17

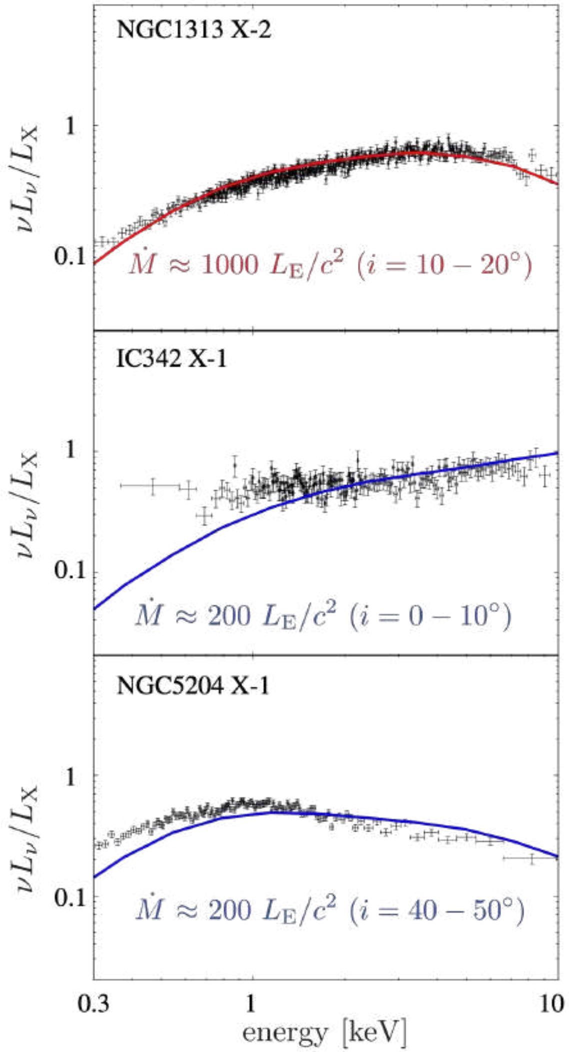
Comparison with ULXs



Monte Carlo
Radiation Transfer:

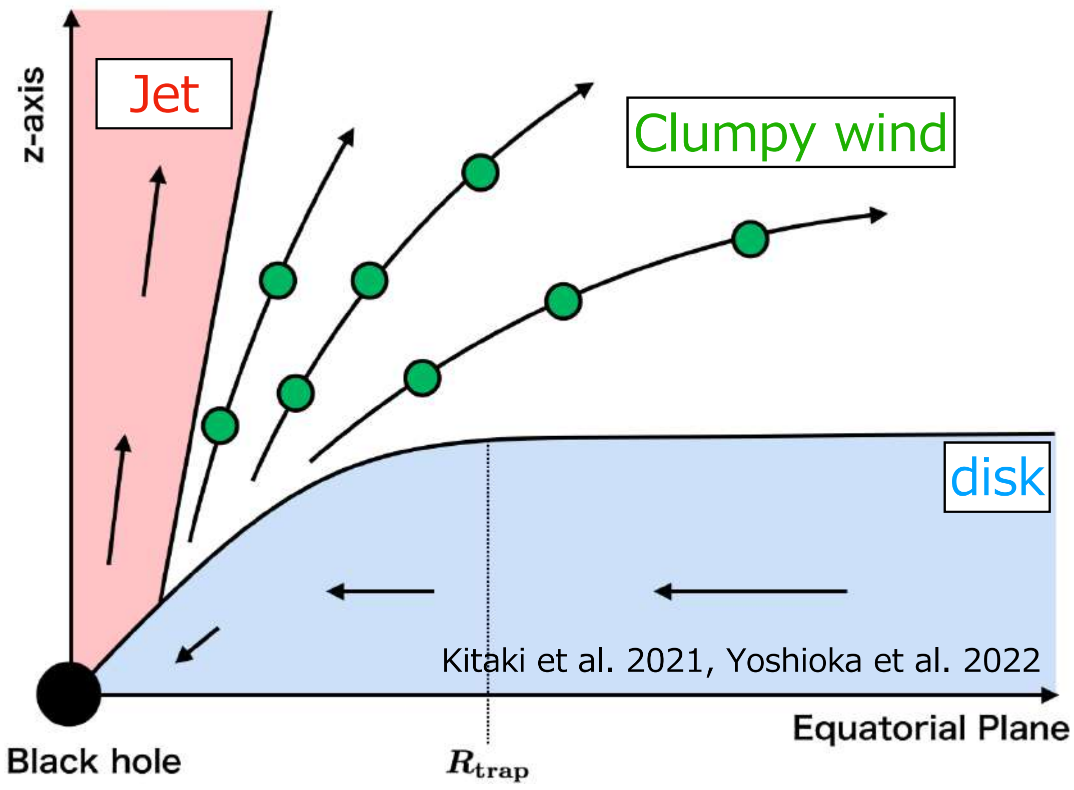
High-energy X-ray photons are produced by the thermal & bulk Comptonization. Simulated spectra nicely fit the observations of ULXs.

Kawashima et al. 2012
(data; Gladstone 2009)



Overall structure of the super-Edd. flows

Schematic picture of the overall structure

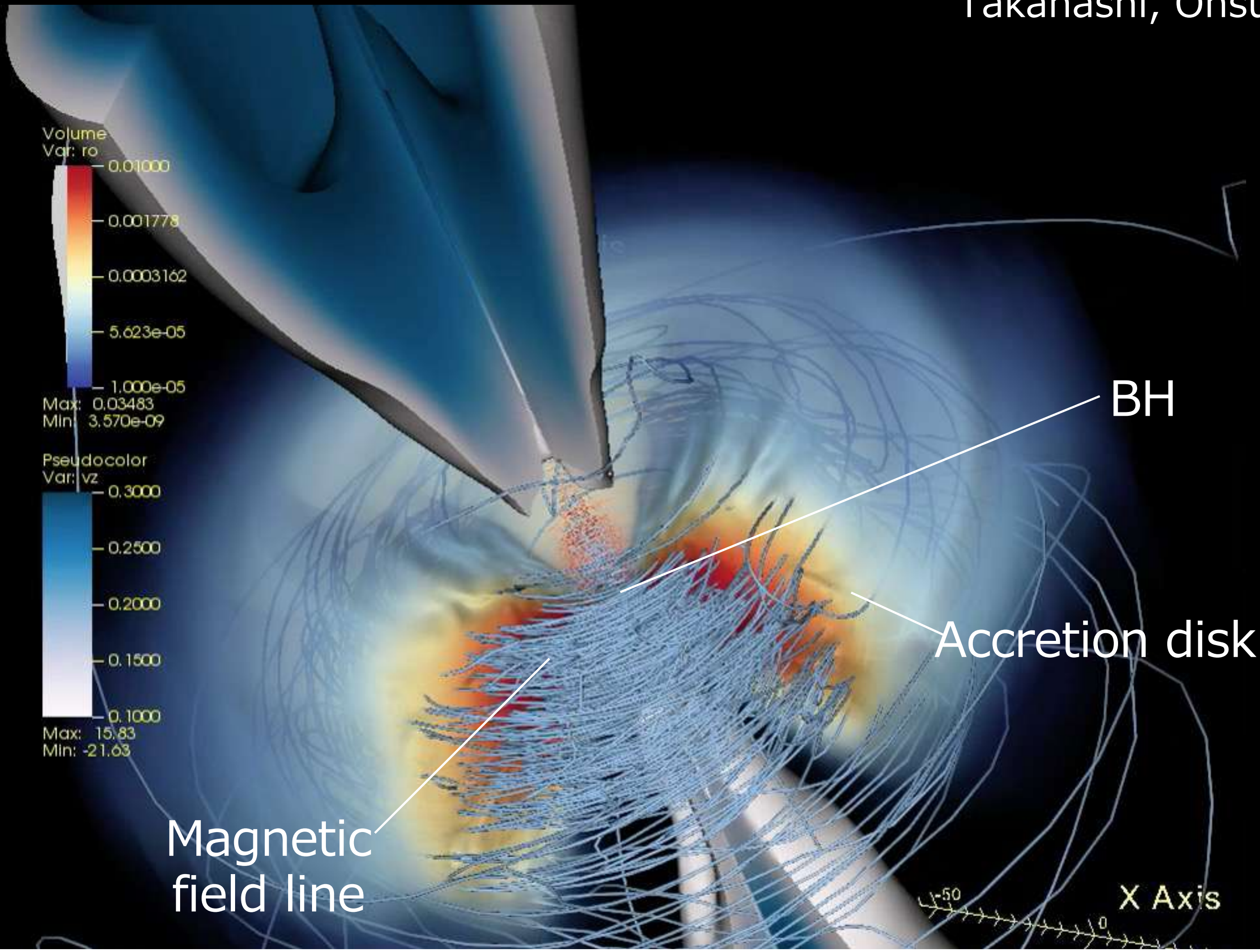


Super-Eddington flows consist of three components;

- ☐ radiation pressure-dominated disk
- ☐ radiatively-driven high-velocity outflow around the rotation axis (jet)
- ☐ radiatively-driven clumpy wind.

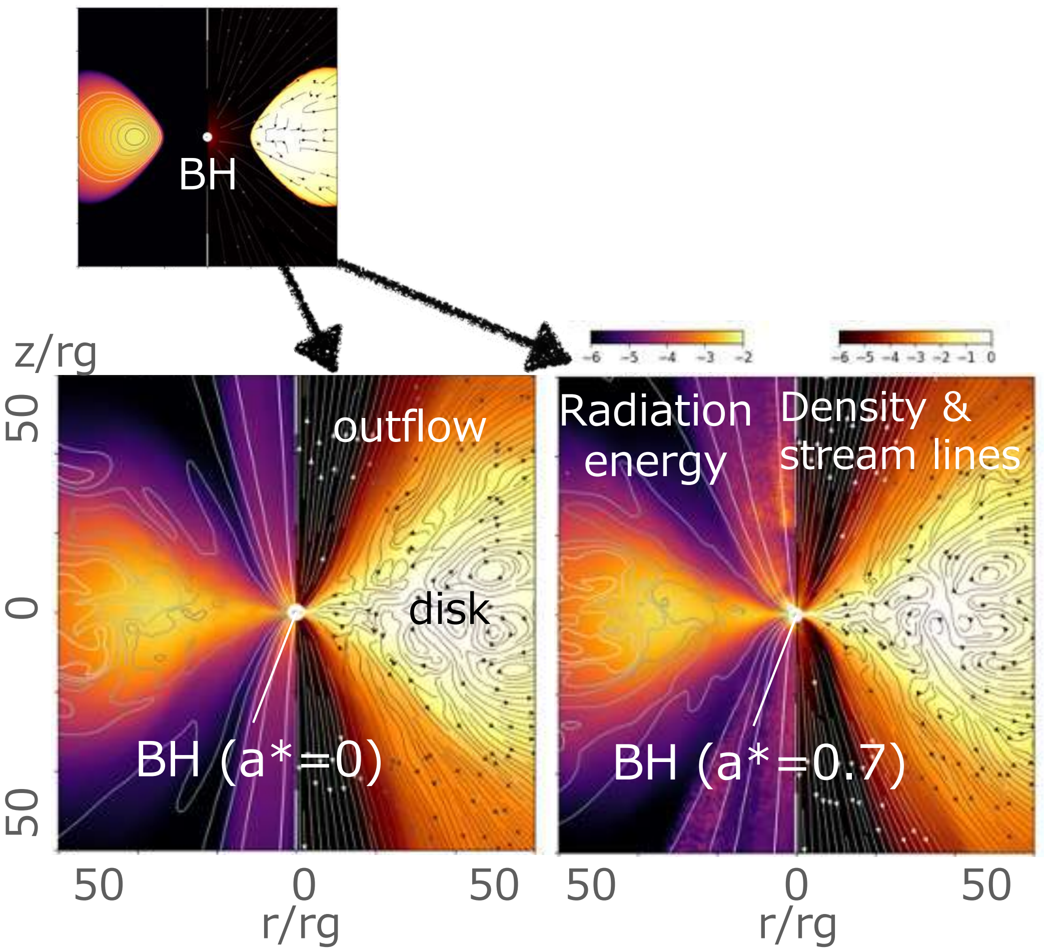
General Relativistic Radiation-MHD simulations

Takahashi, Ohsuga et al. 2016



BZ mechanism in Super-Edd. disk

Utsumi, Ohsuga et al. 2022



Setup

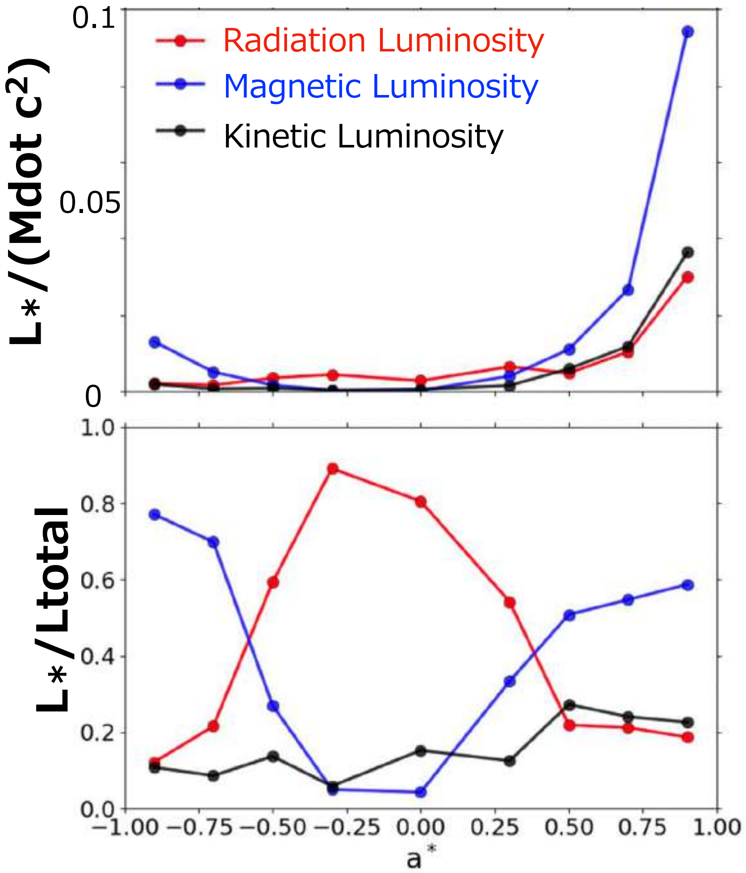
- BH mass: 10Msun
- Initial condition: equilibrium torus with embedded poloidal magnetic field (plasma-beta=100)
- Spin parameter: -0.9, -0.7, -0.5, -0.3, 0, 0.3, 0.5, 0.7, 0.9

Quasi-steady structure

- In all models, the super-Eddington disks (Mdot ~ a few $100L_{Edd}/c^2$) and strong outflows are formed.

* Magnetic field is not so strong (SANE)

Energy Conversion Efficiency

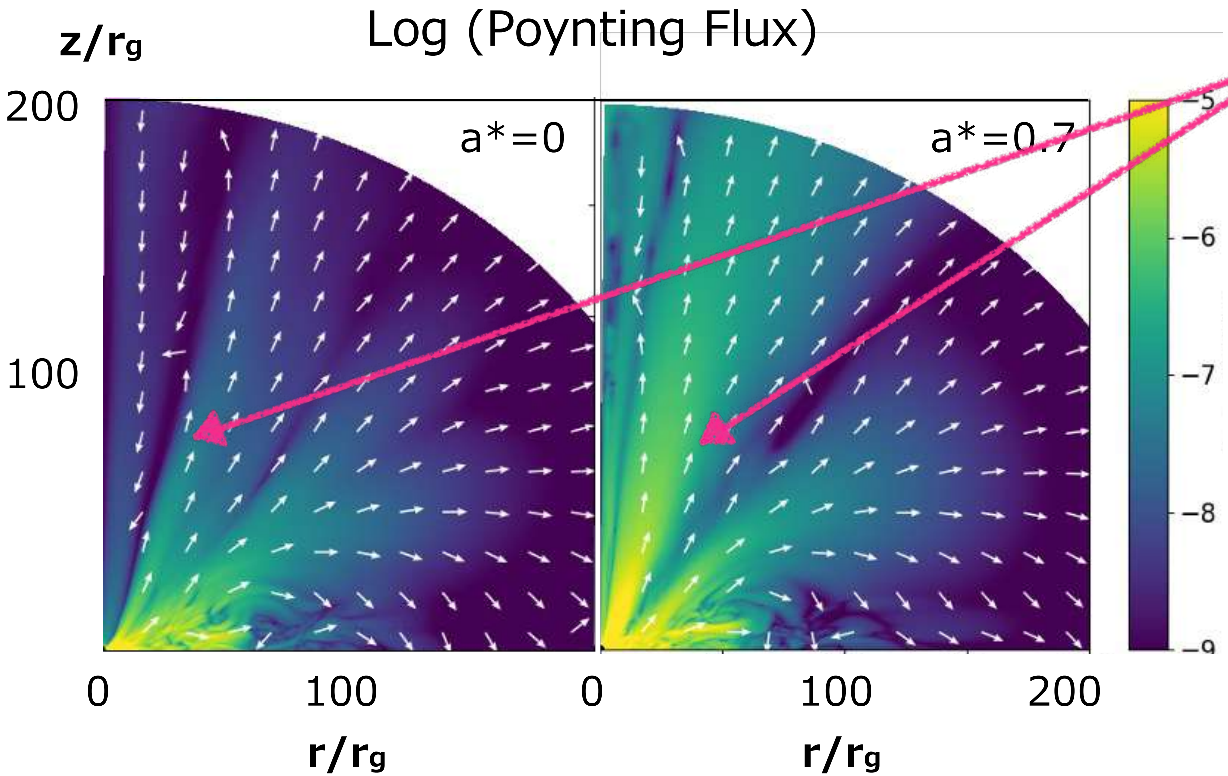


For the case of a*~0, energy is mainly released by the radiation. When |a*| is large, the energy released by the Poynting flux (Magnetic Luminosity) exceeds the Radiation Luminosity.

Radiation luminosity accounts for 80% when a* ~ 0. But the magnetic luminosity is three times larger than the radiation luminosity for the case of a* > 0.5.

See also Sadowski et al 2014, 2019, Bandon 2023

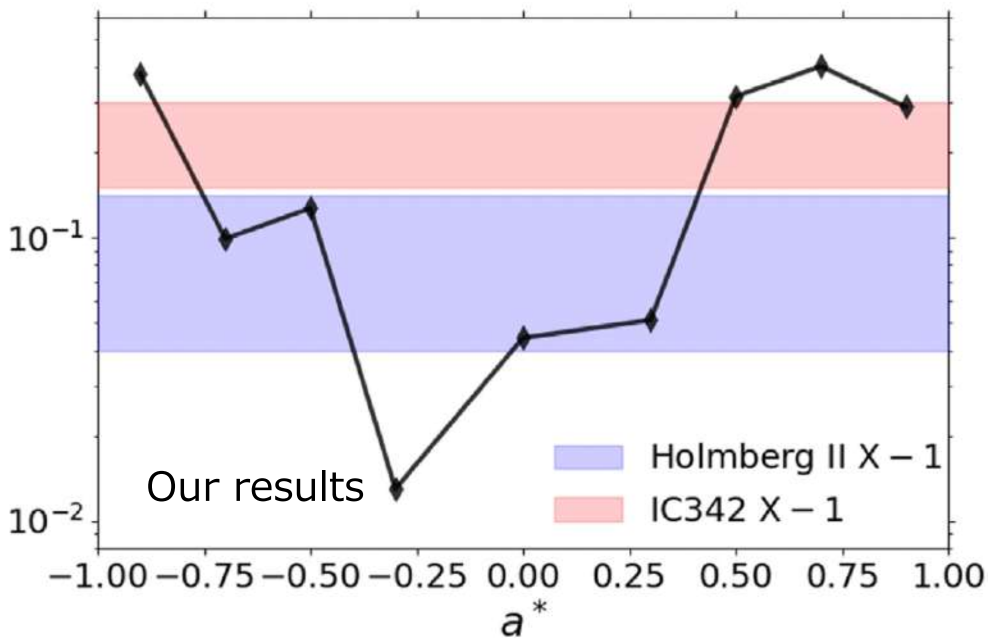
Enhancement of Poynting Flux



The Poynting flux around the rotation axis is stronger for larger |a*|. This is probably caused by Blandford-Znajek (BZ) effect.

Are black holes in ULXs rotating?

Kinetic Luminosity/Isotropic X-ray Luminosity



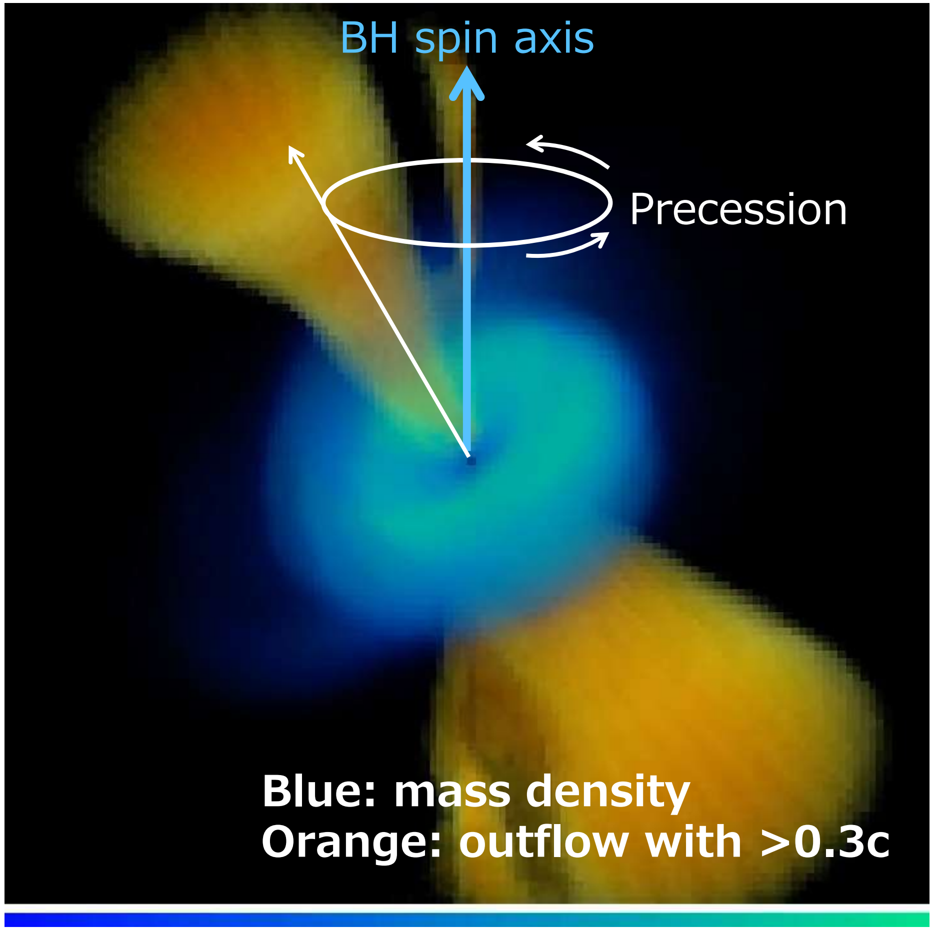
*Isotropic X-rau Luminosity:
Radiation luminosity observed by face-on observer.

In our results, the ratio of the kinetic luminosity to isotropic X-ray luminosity tends to increase with |a*|.

Thus, rapidly (slowly) rotating black hole probably exist in IC342 X-1 (Holmberg II X-1).

Lense-Thirring Precession of Super-Edd. disk

Asahina & Ohsuga submitted



Setup

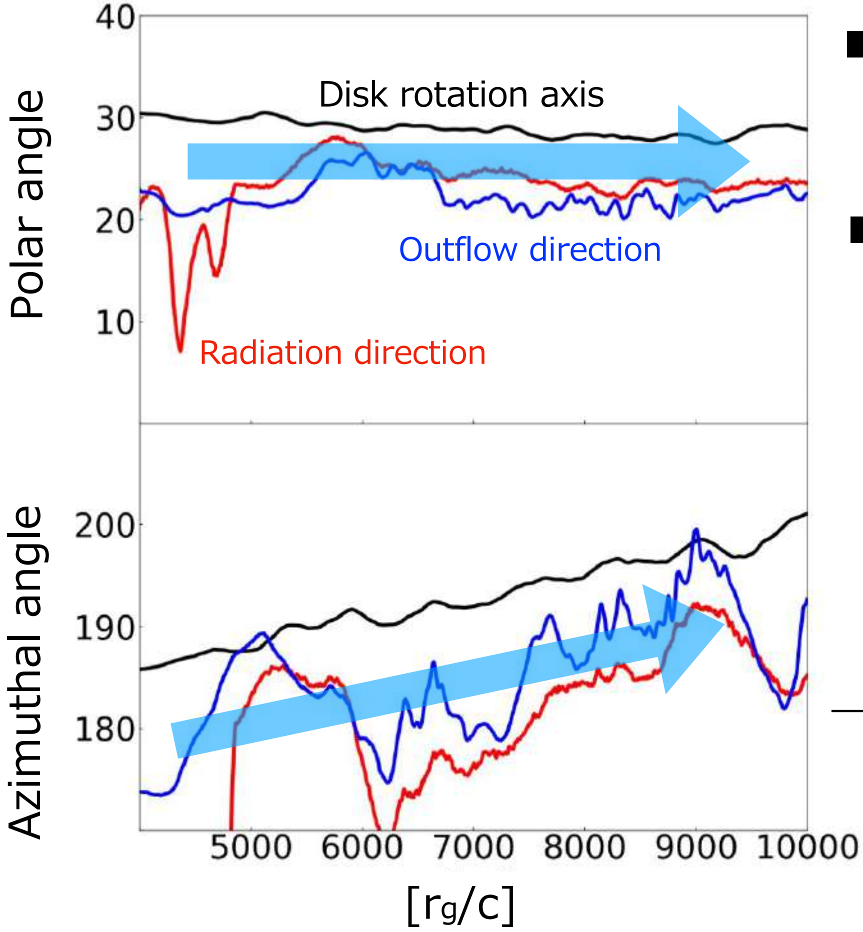
- BH mass: 10Msun
- Initial condition: equilibrium torus with embedded poloidal magnetic field (plasma-beta=100) tilted **30 degree**.
- Spin parameter: **0.9**

Inflow-outflow structure

- The super-Eddington disk, which is tilted and twisted, forms.
- Strong outflows are also formed.

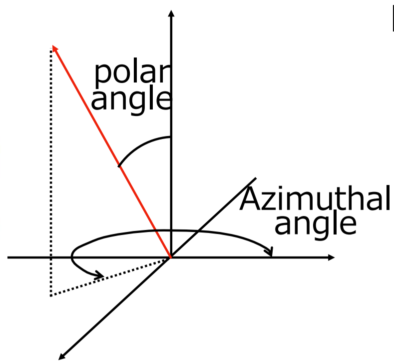
- Accretion rate: several **100 L_{Edd}/c^2**
- Radiation Luminosity: **several L_{Edd}**
- Kinetic Luminosity: **several L_{Edd}**

Precession of disk, outflow, radiation



- The super-Eddington disk exhibits the precession motion.

- The gas and radiation is mainly ejected around the rotation axis of the disk (~30°), rather than around the spin axis of the BH (0°).

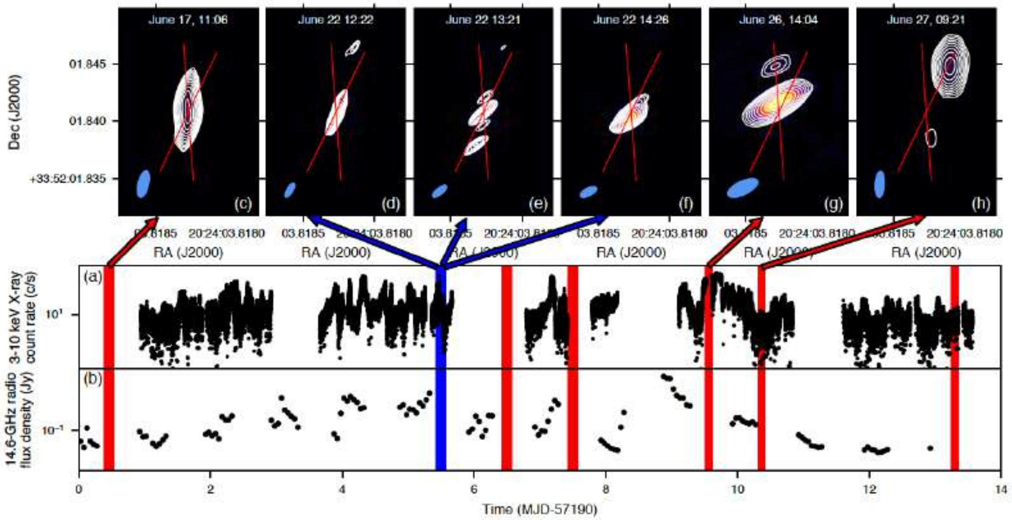


- The direction of outflow and radiation also changes according to the precession motion of the disk. However, there is about 10° delay from the rotational axis of the disk.

Comparison with observations

[1] Quasi periodic oscillations of ULXs:
The typical timescale of the precession is ~9sec for the case of stellar mass BH.
This timescale is consistent with the QPOs observed in some ULXs.

[2] Precession of jets in V404 Cygni:
The direction of jet is changing with time in V404 Cygni
(Miller-Jones et al. 2019).
Such behavior is consistent with our calculations.



Summary

- Basic features of super-Eddington flows are revealed by Radiation-HD/Radiation-MHD simulations. The super-Eddington flows consist of the (1)radiation pressure-supported disk, (2)the radiatively-driven high-velocity outflows around toe rotation axis, (3) and clumpy disk winds with wide opening angle.
- Our simulations results can explain the basic features of ULXs, Large X-ray luminosity, X-ray spectra, end so on.
- BZ effect and Lense-Thirring precession in the super-Eddington accretion has been confirmed by our GR-Radiation-MHD simulations.

For neutron stars; Takahashi & Ohsuga 2017, Takahashi, Ohsuga, et al. 2018, Inoue, Ohsuga et al. 2023