Relativistic Fluids around Compact Objects
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Numerical Simulations of Supercritical Accretion Flows Around a Compact Object

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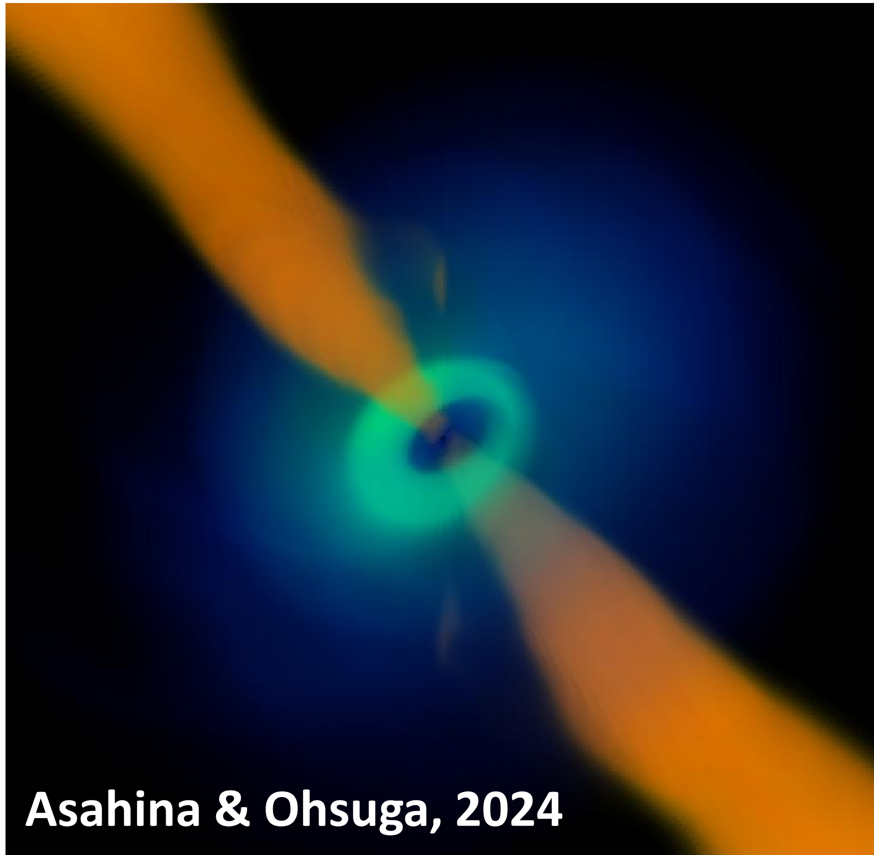

Contents

- Introduction: Black hole accretion disk
- Blandford-Znajek Mechanism

  : effects of the general relativity and magnetic field

- Lense-Thirring Effect

  : effects of the general relativity for tilted accretion disk

- Machine learning using simulation results

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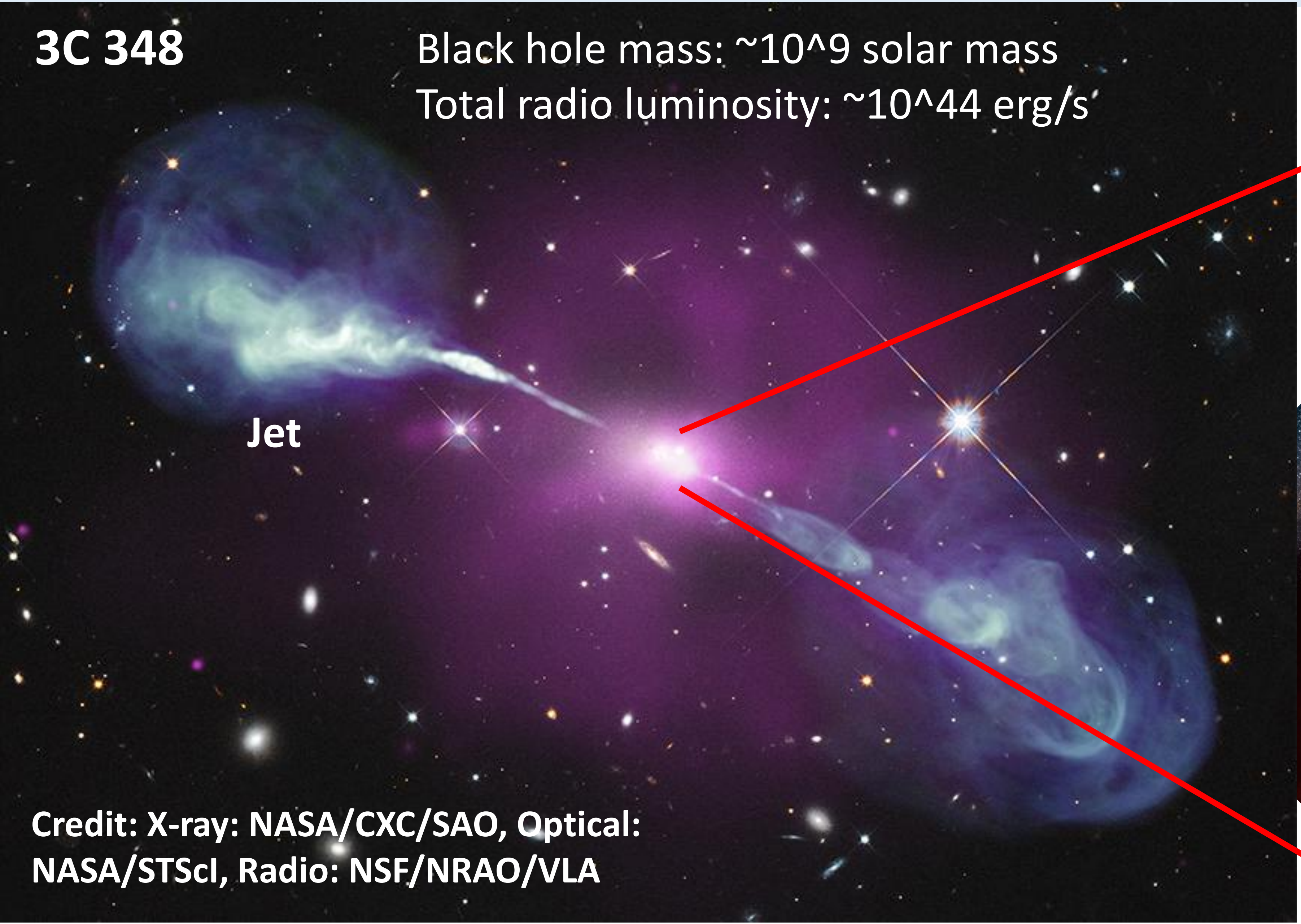
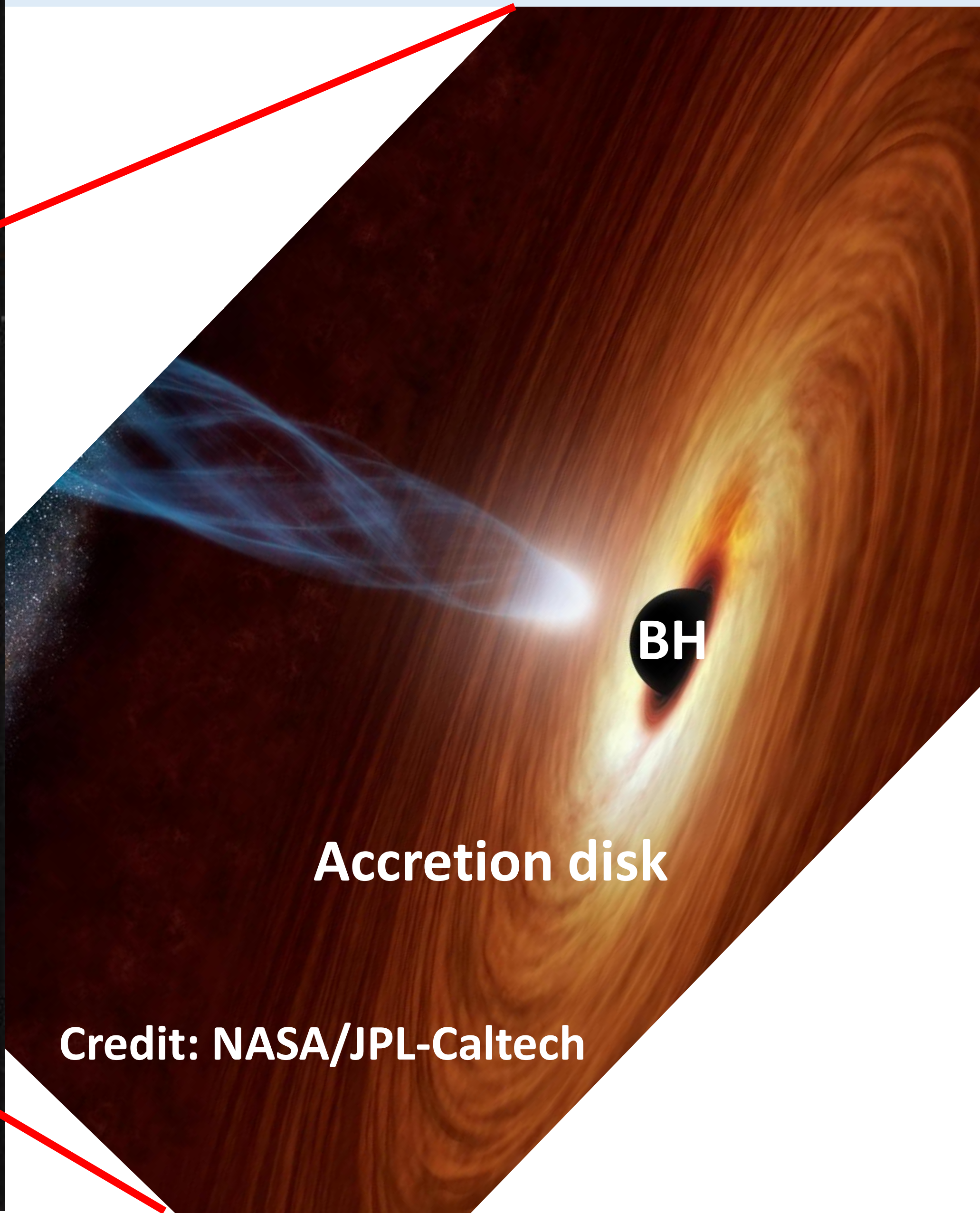
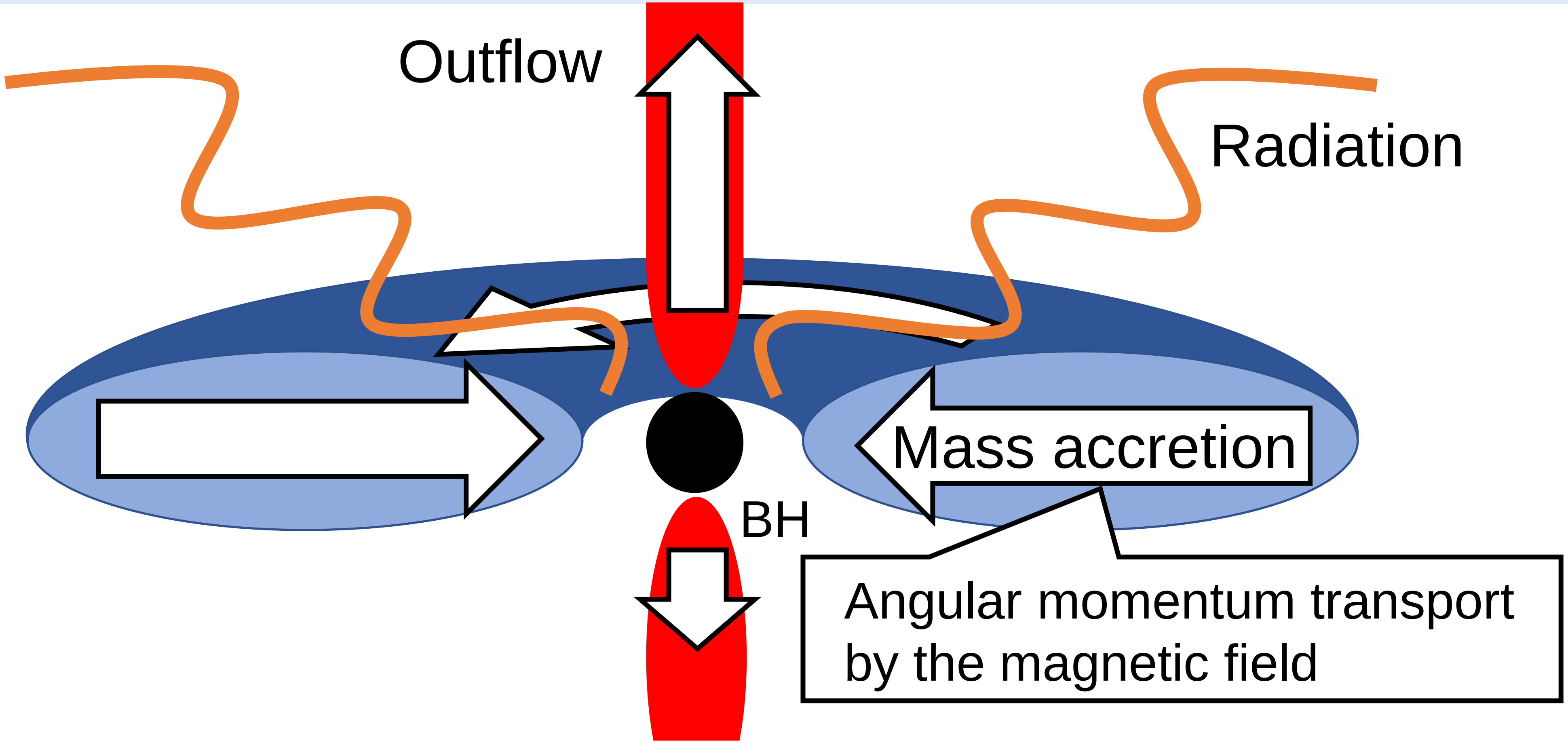
Black Hole (BH) is a Powerful Energy Source





BH Accretion Disks

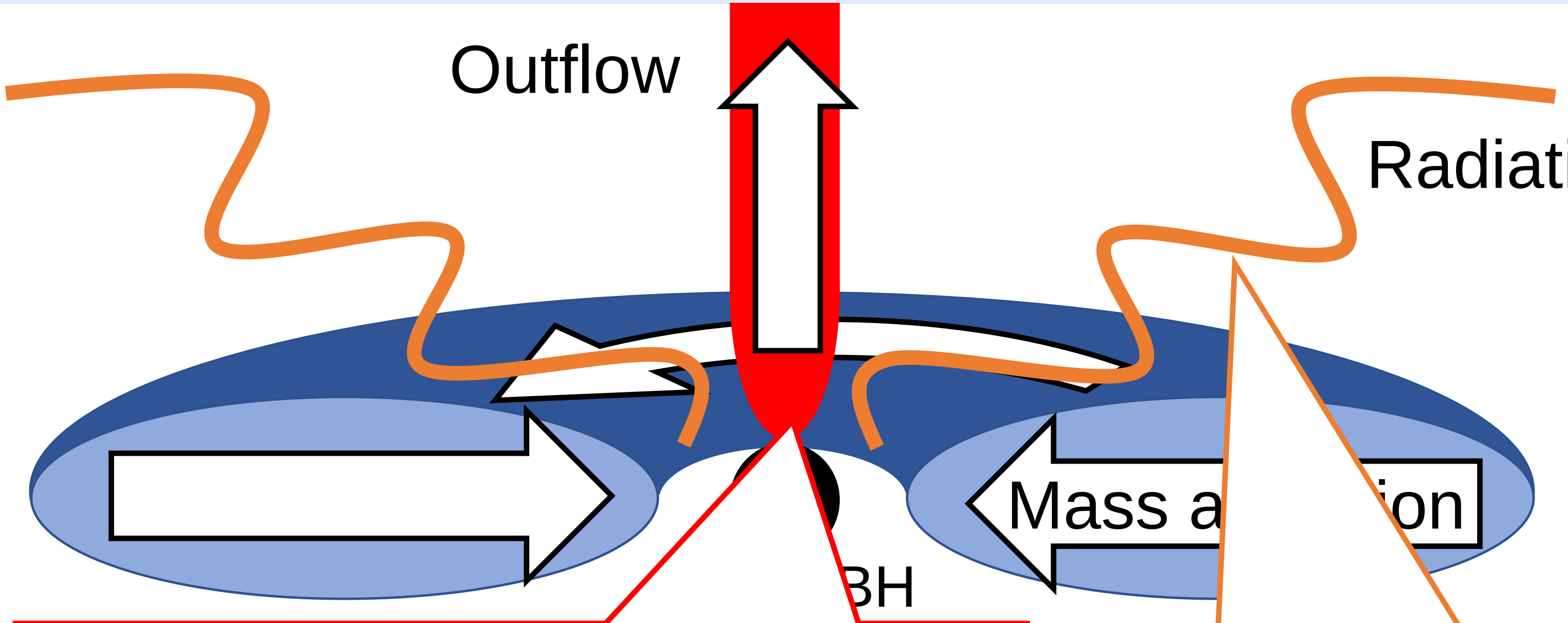


Conversion of energy

Gravitational energy
↓
Magnetic and thermal energy
↓
Radiation energy

- Rotating gas around the BH forms an accretion disk
- A part of the released gravitational energy is converted to the radiation energy
- **We need to include the effect of the radiation** when the mass accretion rate is high

BH Accretion Disks



Conversion of energy

Gravitational energy

↓

Magnetic and thermal energy

↓

iation energy

What is the acceleration mechanism?
What determine the structure and velocity of the outflow?
How much energy is released?

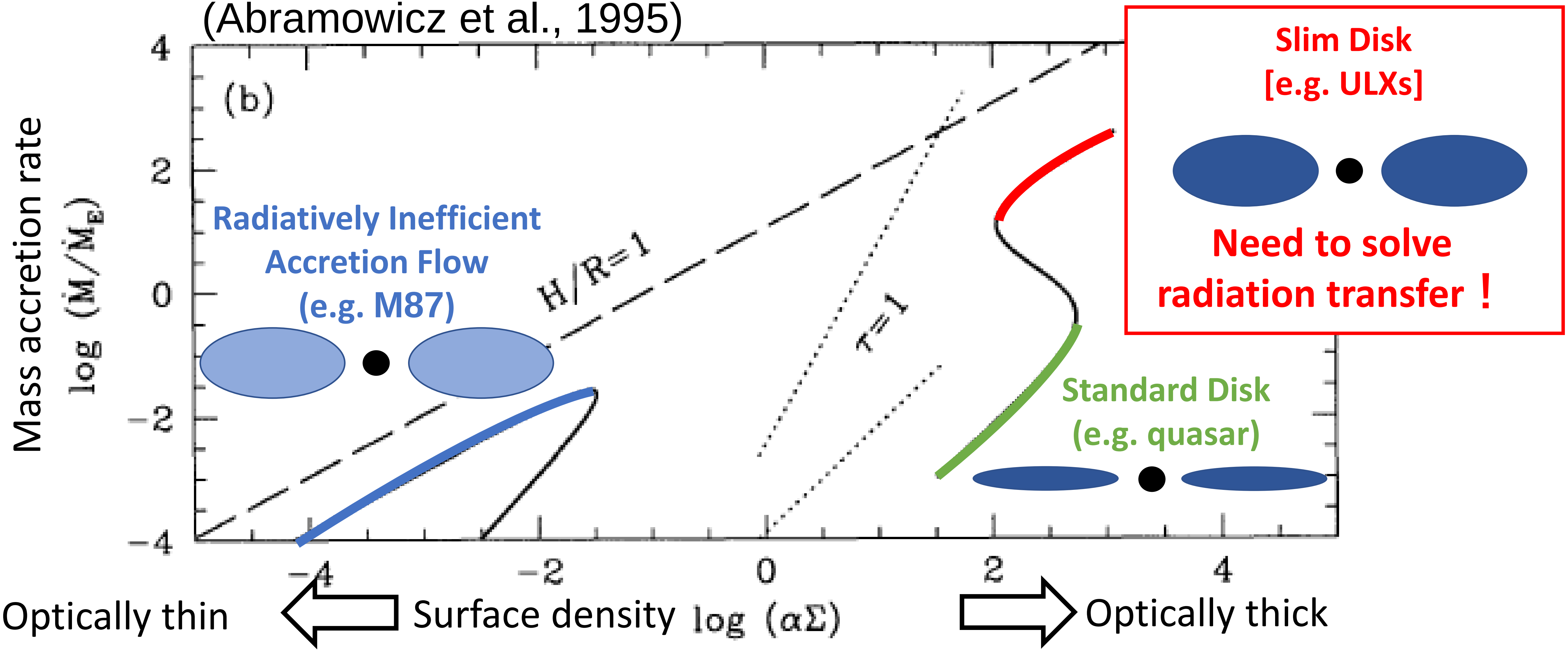
How much is the luminosity?
How does the radiation affect the outflow and accretion disks?

tional energy is converted to the radiation energy

ect of the radiation when the mass accretion rate is high

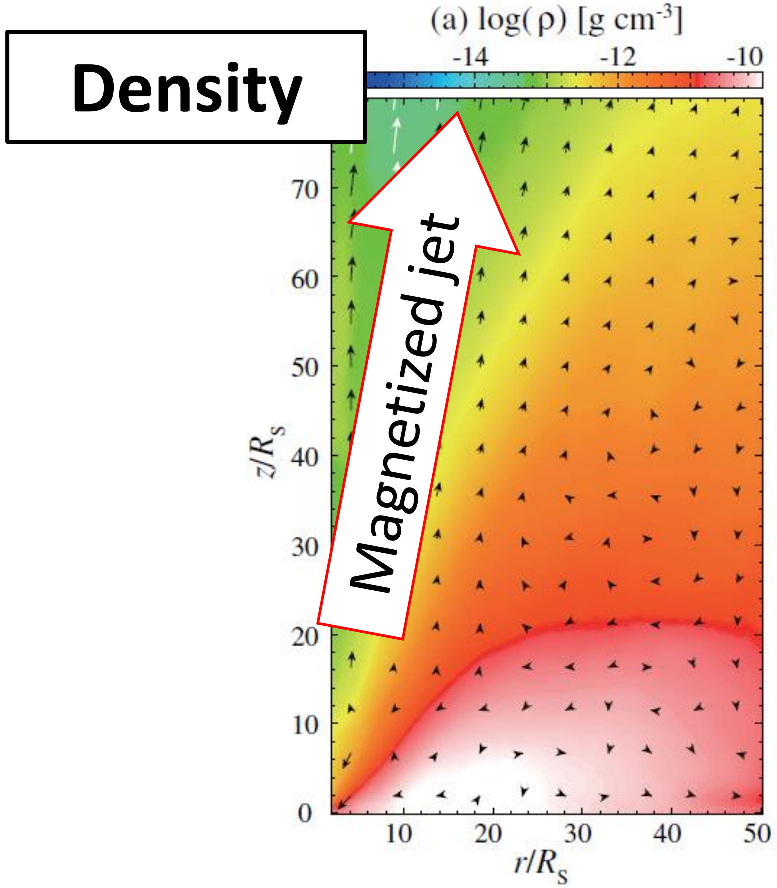
Three Accretion Modes

Three thermal equilibrium accretion modes have been achieved (Abramowicz et al., 1995)

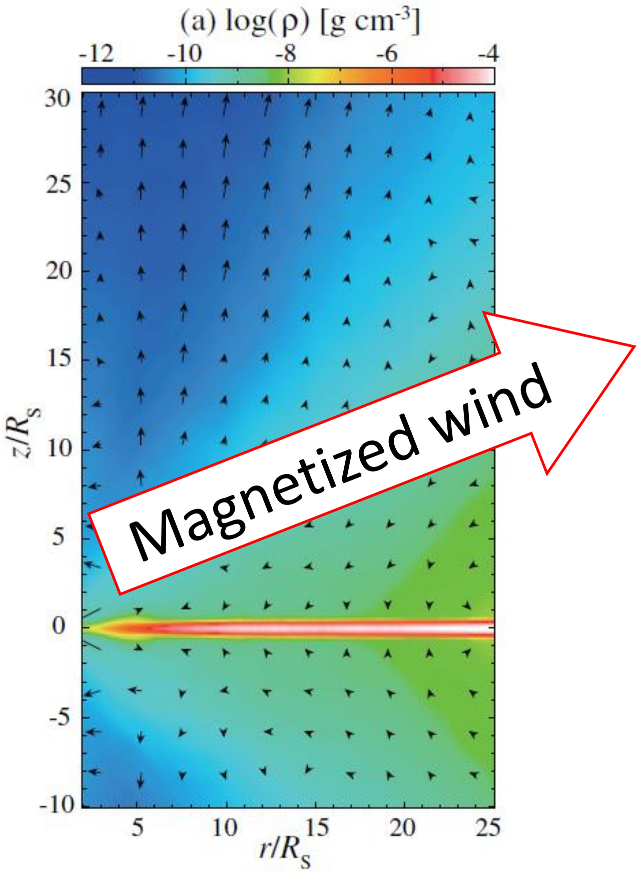


Radiation MHD Simulations of Three Accretion Modes

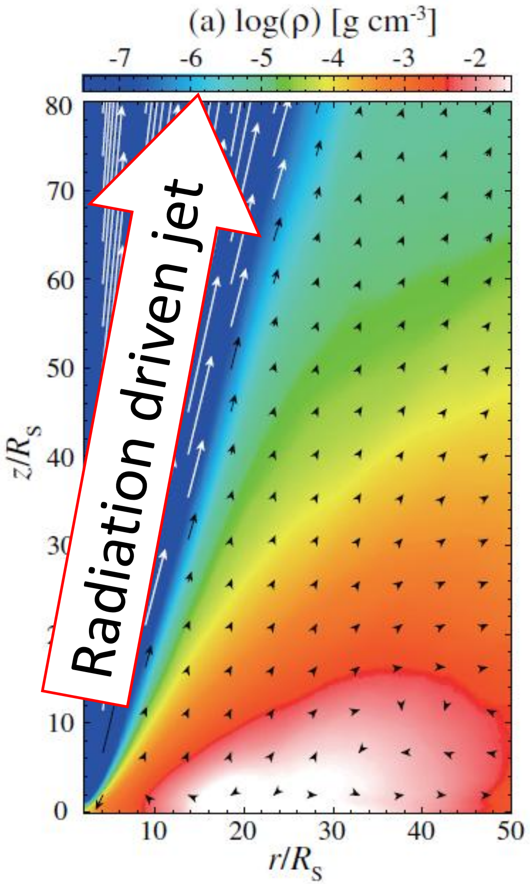
Radiatively Inefficient Accretion Flow



Standard Disk



Slim Disk



low → **high**

Mass accretion rate

Ohsuga et al. (2009,2011)

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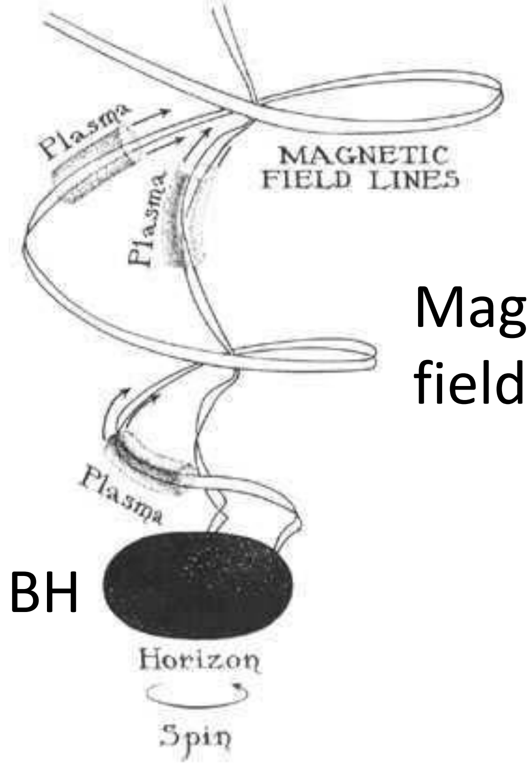
Blandford-Znajek (BZ) Mechanism

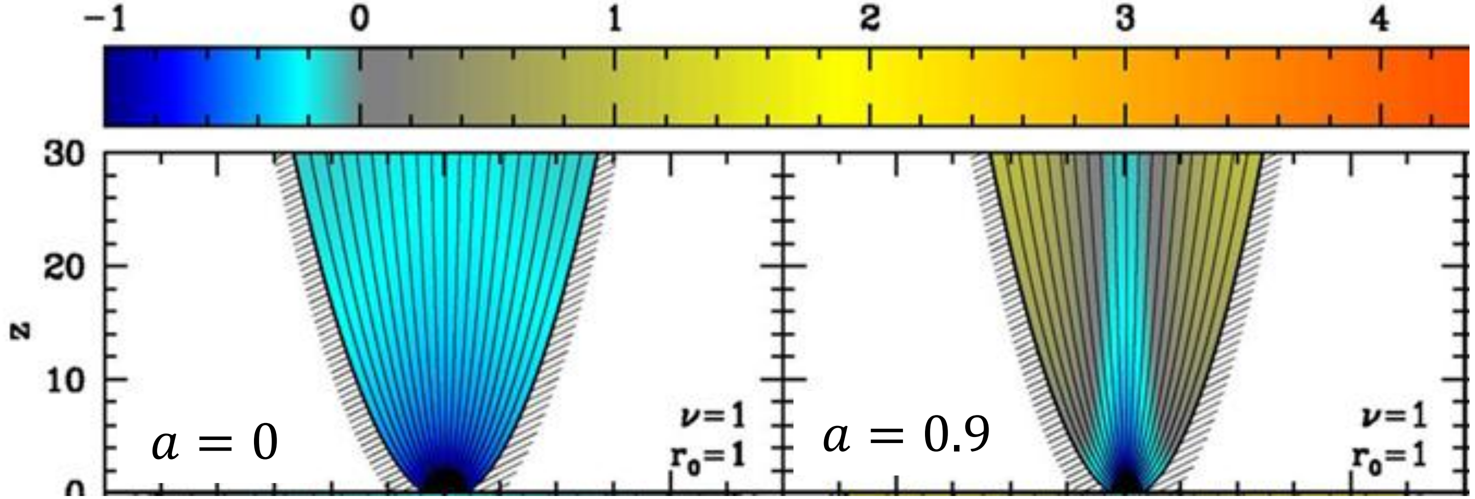
A mechanism for the extraction of energy from a spinning black hole through the magnetic field (Blandford & Znajek, 1977)



K. Thorne, Black Holes and Time Warps (W.W.Norton and Company, 1994).

Tchekhovskoy+(2010) performs the numerical simulation focusing on the jet region

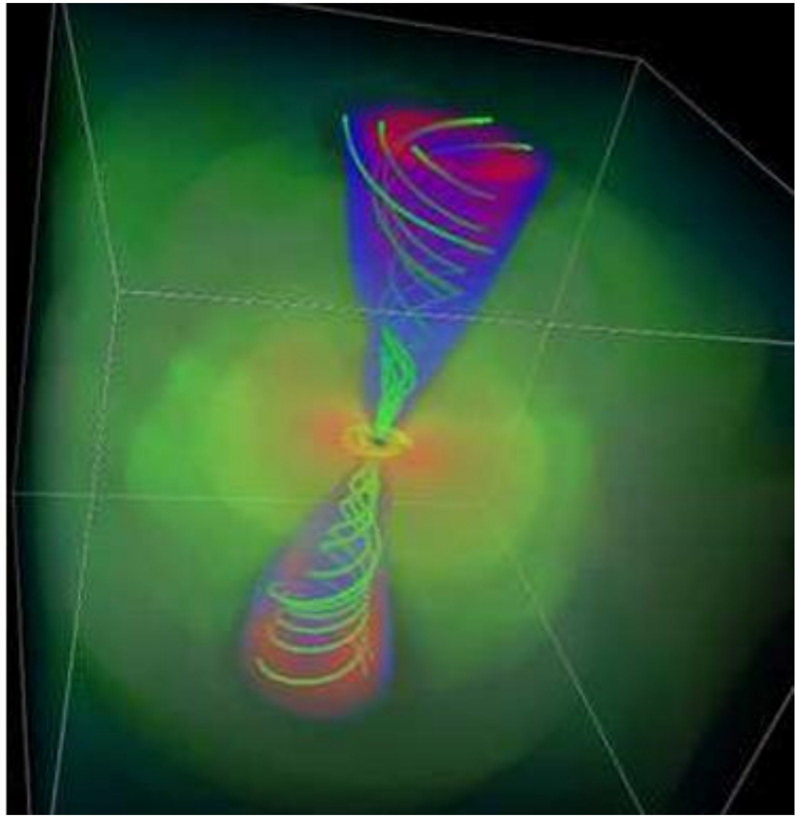
Radial four-velocity u^r



They reveal the jet power is proportional to Ω_{H}^2, $\Omega_{\mathrm{H}} = a/r_{\mathrm{H}}(a)$ is the angular frequency of the BH (when $a \ll 1$, the jet power $\propto a^2$)

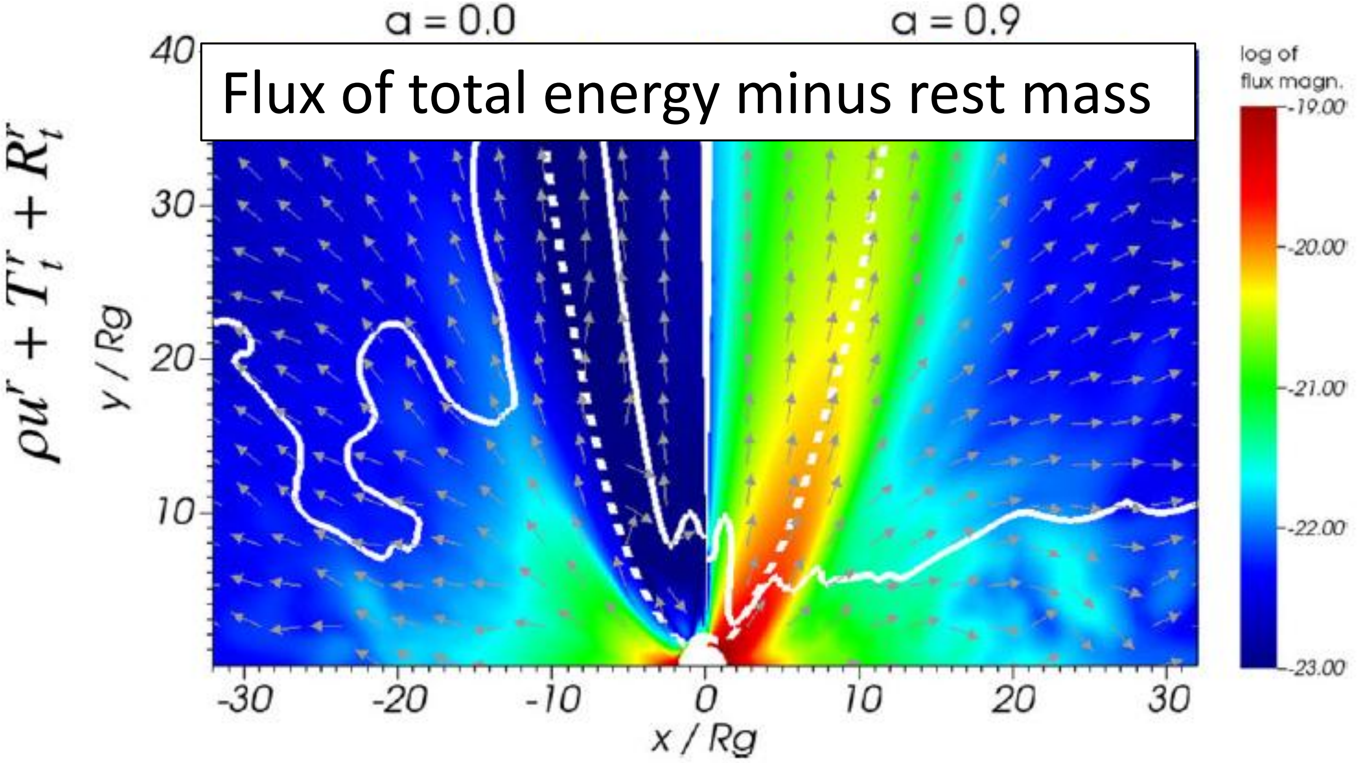
GRMHD and GRRMHD simulations

GRMHD simulations with the spin of 0.9 (McKinney and Blandford, 2009)



This simulation also shows that the BH spin is important for the formation of the powerful jet.

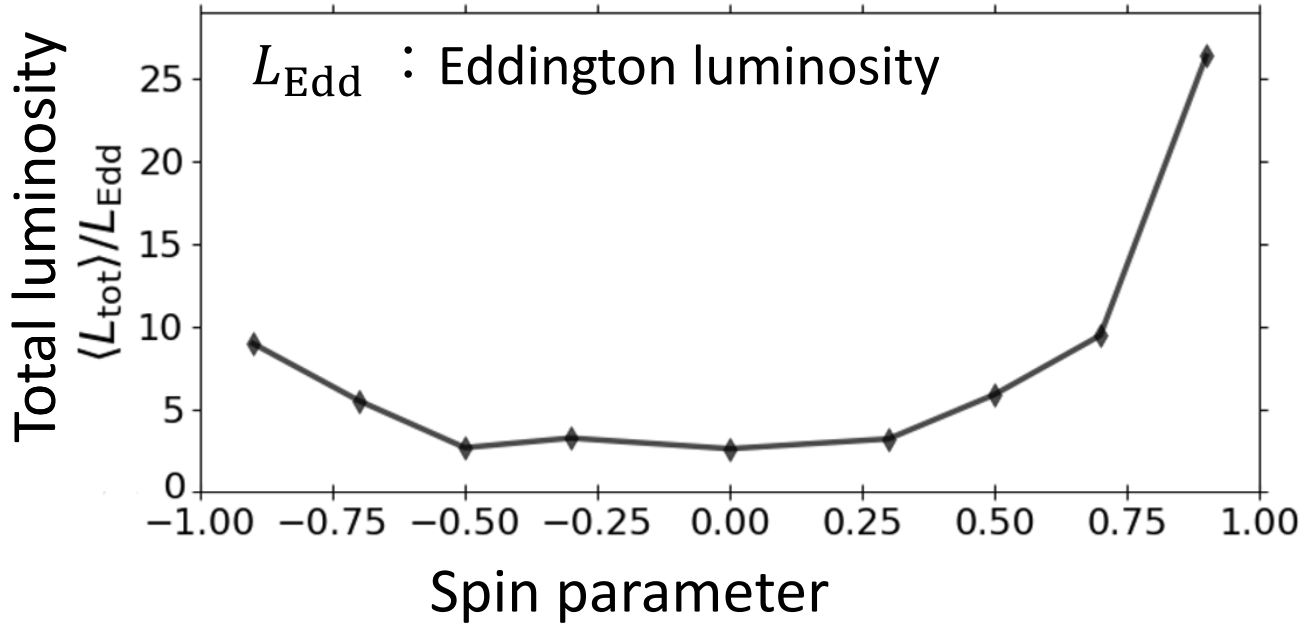
GRRMHD simulations with the spin of 0 and 0.9 (Sadowski et al. 2014)

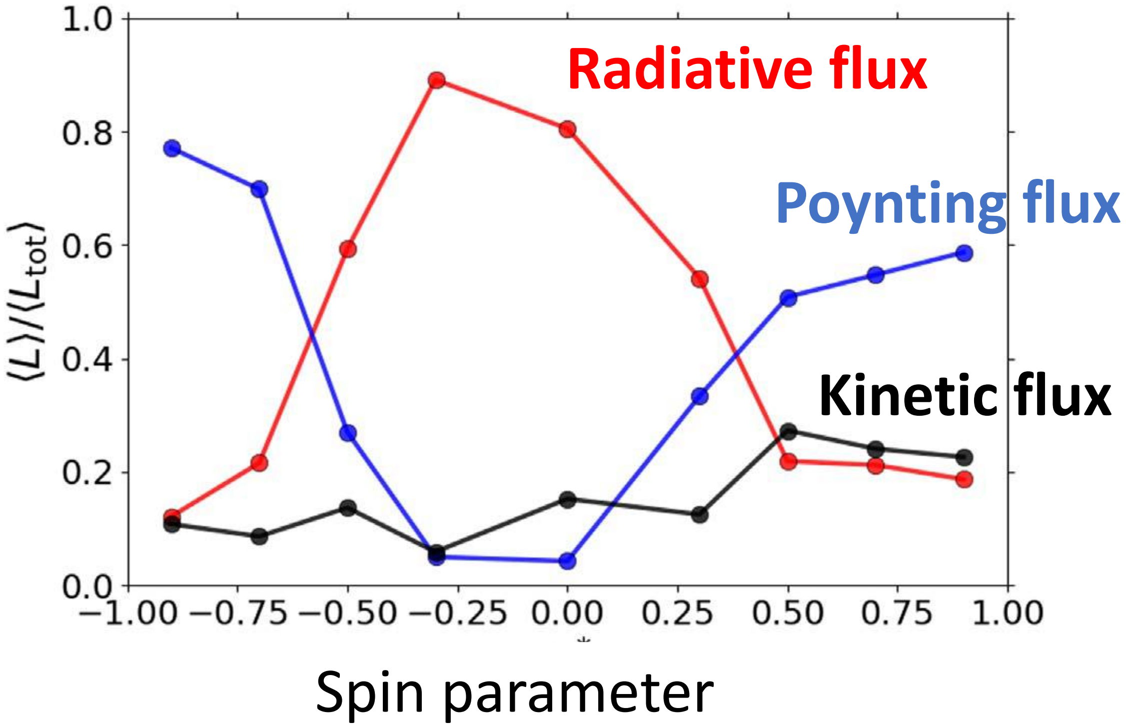


The Poynting flux which fills the jet region presumably as a consequence of the BZ mechanism

Dependence on BH spin

GRRMHD simulations with various spin parameters（Utsumi et al., 2022）





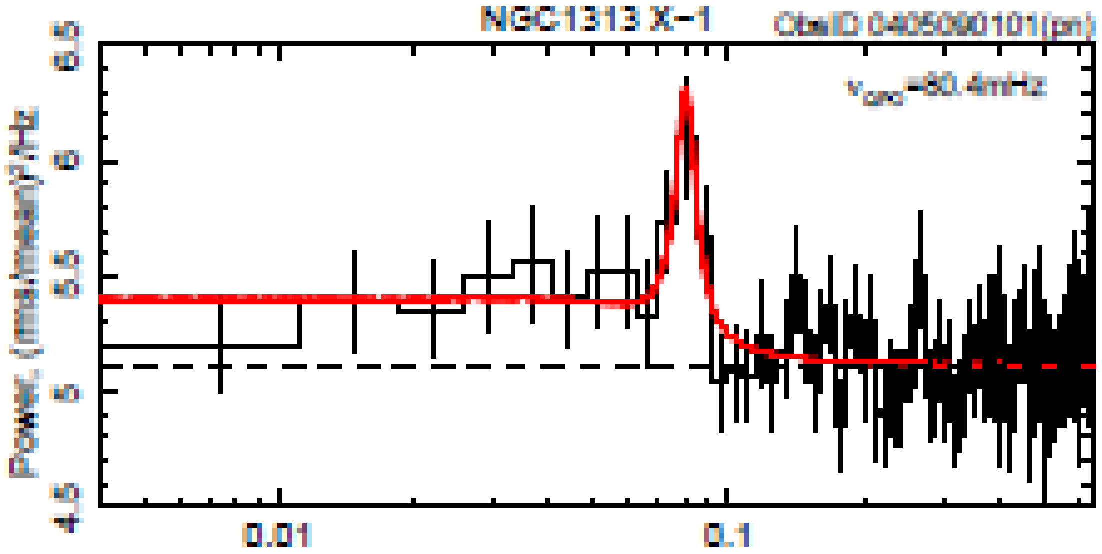
- The total luminosity and ratio of the magnetic energy becomes larger increasing with the absolute value of the spin parameter due to BZ mechanism
- Spinning black holes can be brighter and form stronger jet

Contents

Quasi-Periodic Oscillations (QPOs) for Ultra Luminous X-ray Sources (ULXs)

Ultra Luminous X-ray Sources (ULXs):

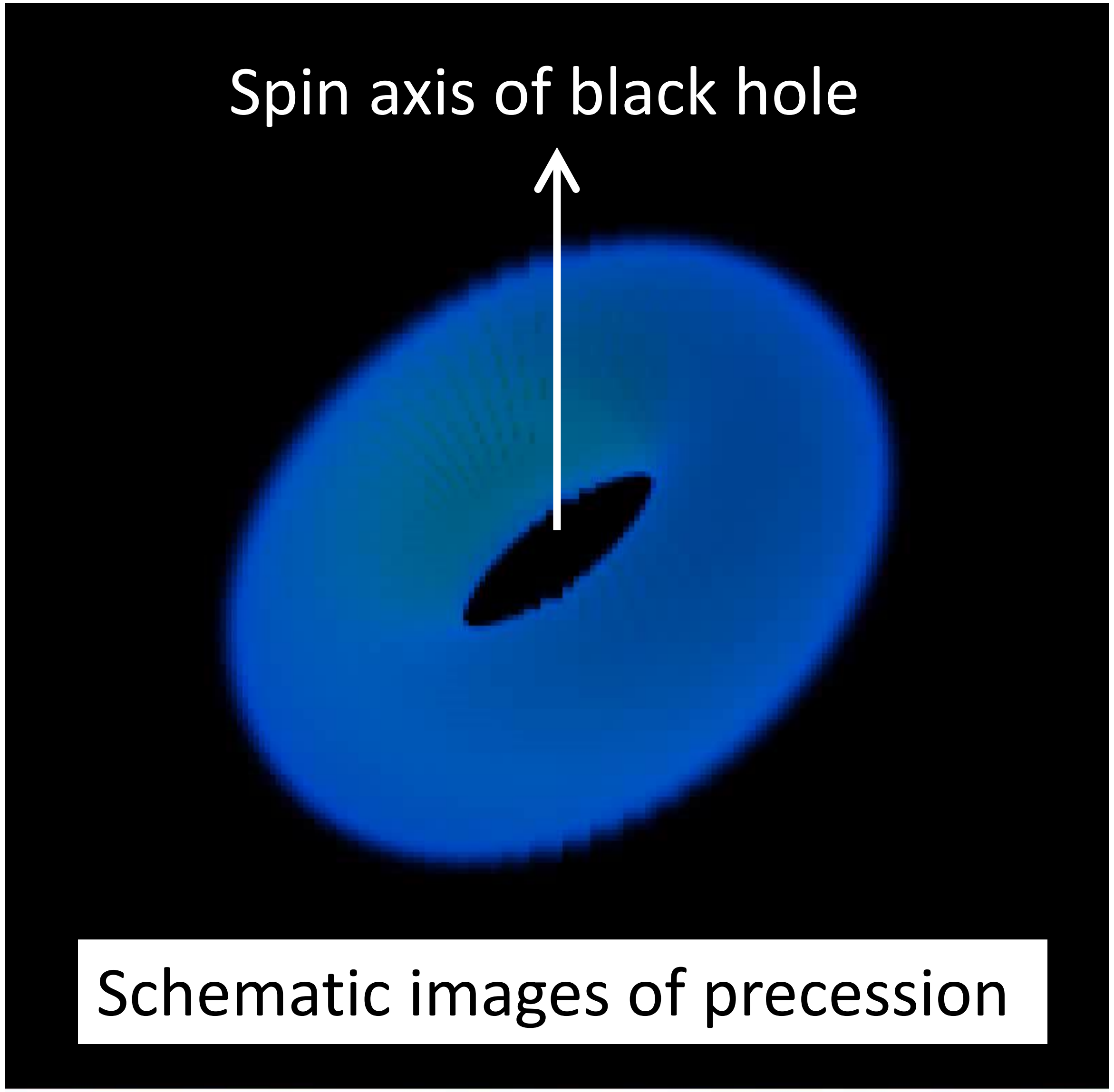
Astronomical sources exceed 10^{39} erg/s which is the Eddington luminosity for $10M_{\odot}$ BH



Power spectrum of NGC1313 X-1 (Atapin et al. 2019)

- Quasi-Periodic Oscillations (QPOs) with oscillation frequencies in the range of about 0.01 to 1 Hz have been observed in ULXs
- The left figure illustrates the power density spectra of NGC1313 X-1 as an example, showing a peak at around 80 mHz
- **QPOs could be caused by the precession of the accretion disk due to Lense-Thirring effect**

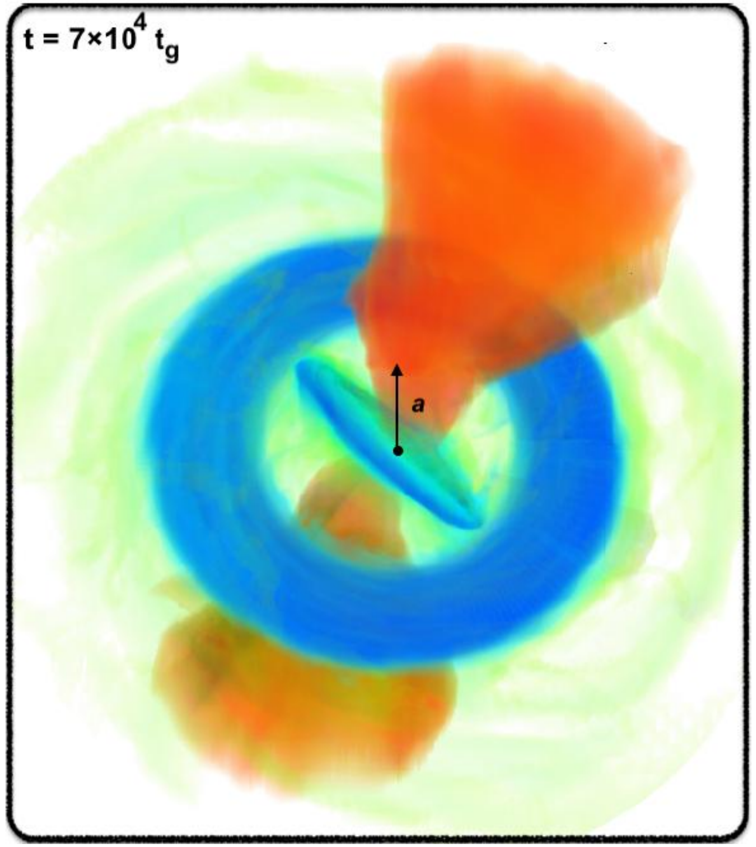
Lense-Thirring Effect



- When the spin axis of a black hole does not align with the rotational axis of the accretion disk, the accretion disk precess due to the frame-dragging (Lense-Thirring effect)
- The disk precession can lead to QPOs as the inclination angle changes periodically
- It is also a potential factor contributing to the precessing jet

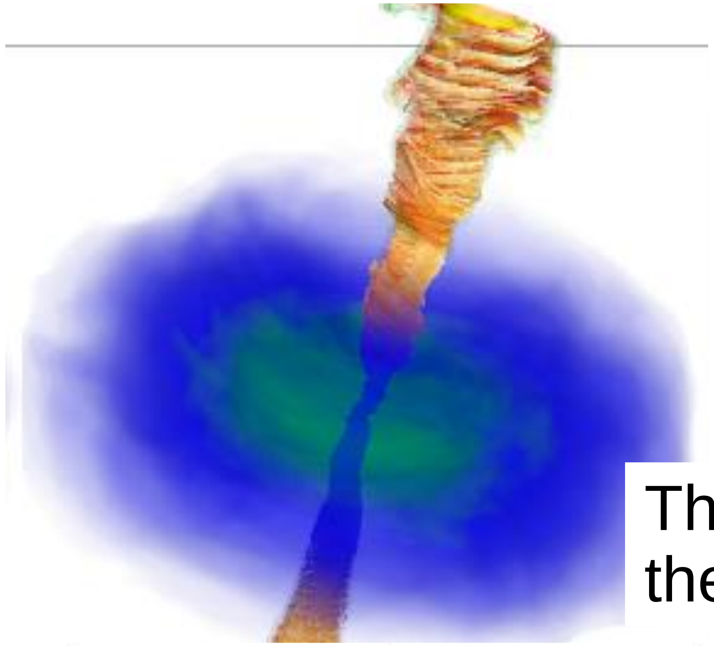
GRMHD simulations of Tilted Disks

GRMHD simulations of tilted **thin** disk (Liska et al. 2019)

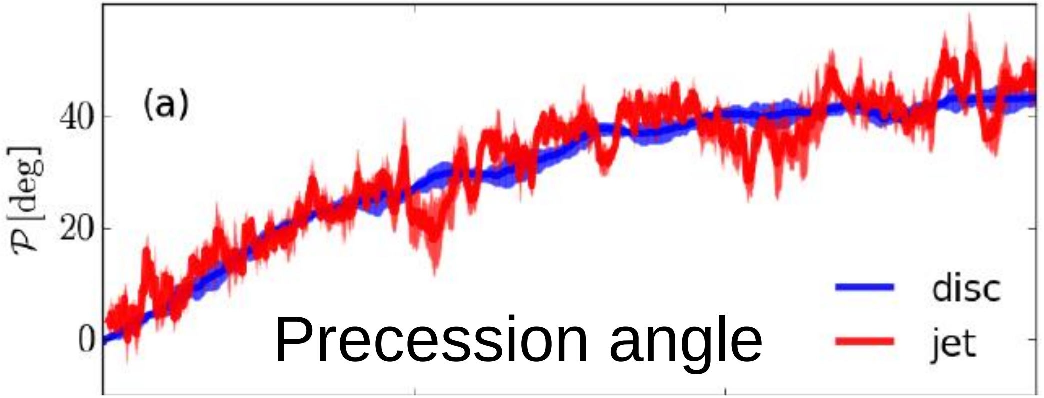


A rapidly precessing inner sub-disk forms surrounded by a slowly precessing outer sub-disk.

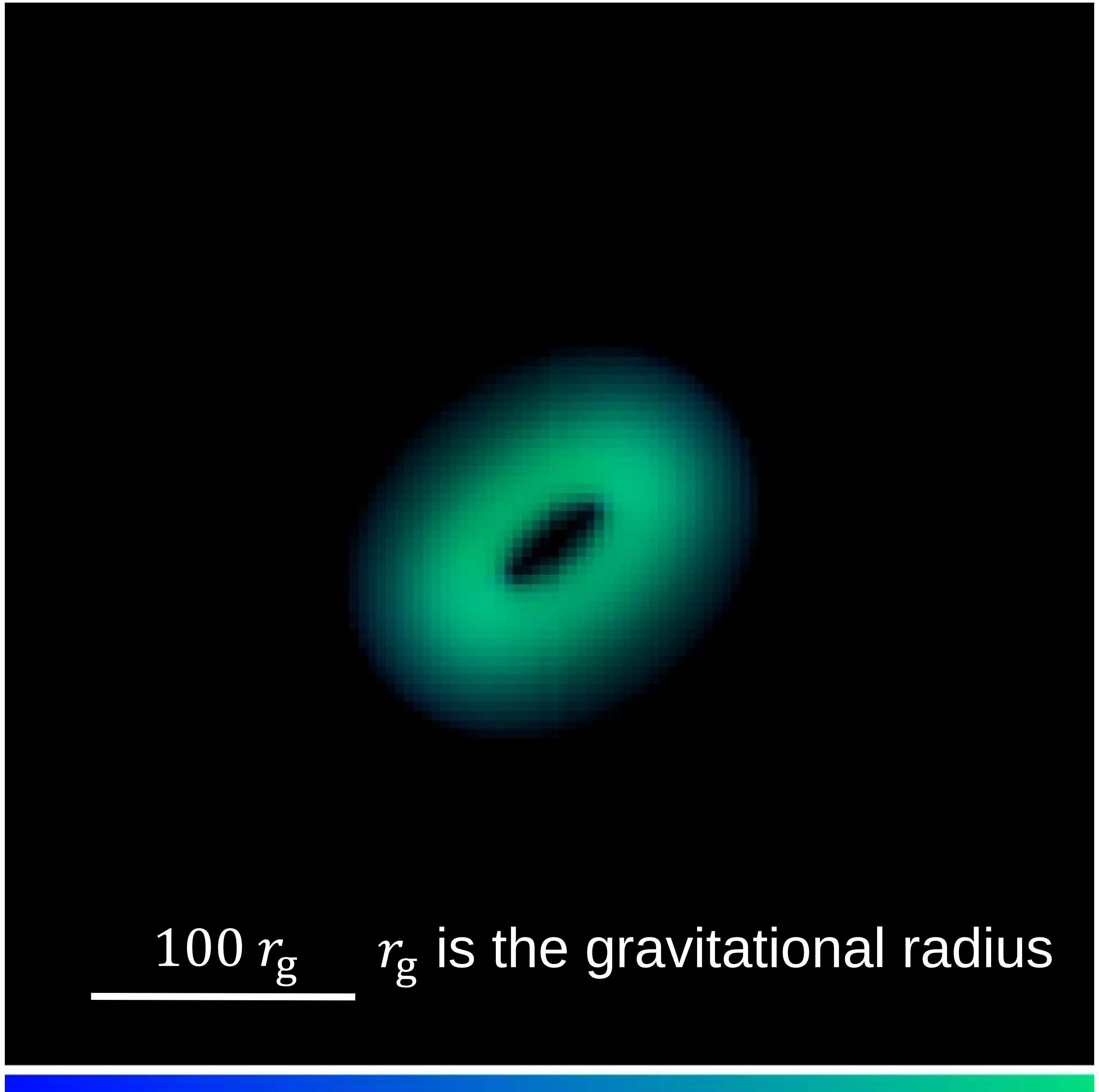
GRMHD simulations of tilted **thick** disk (Liska et al. 2018)



The jet precesses with the disk precession



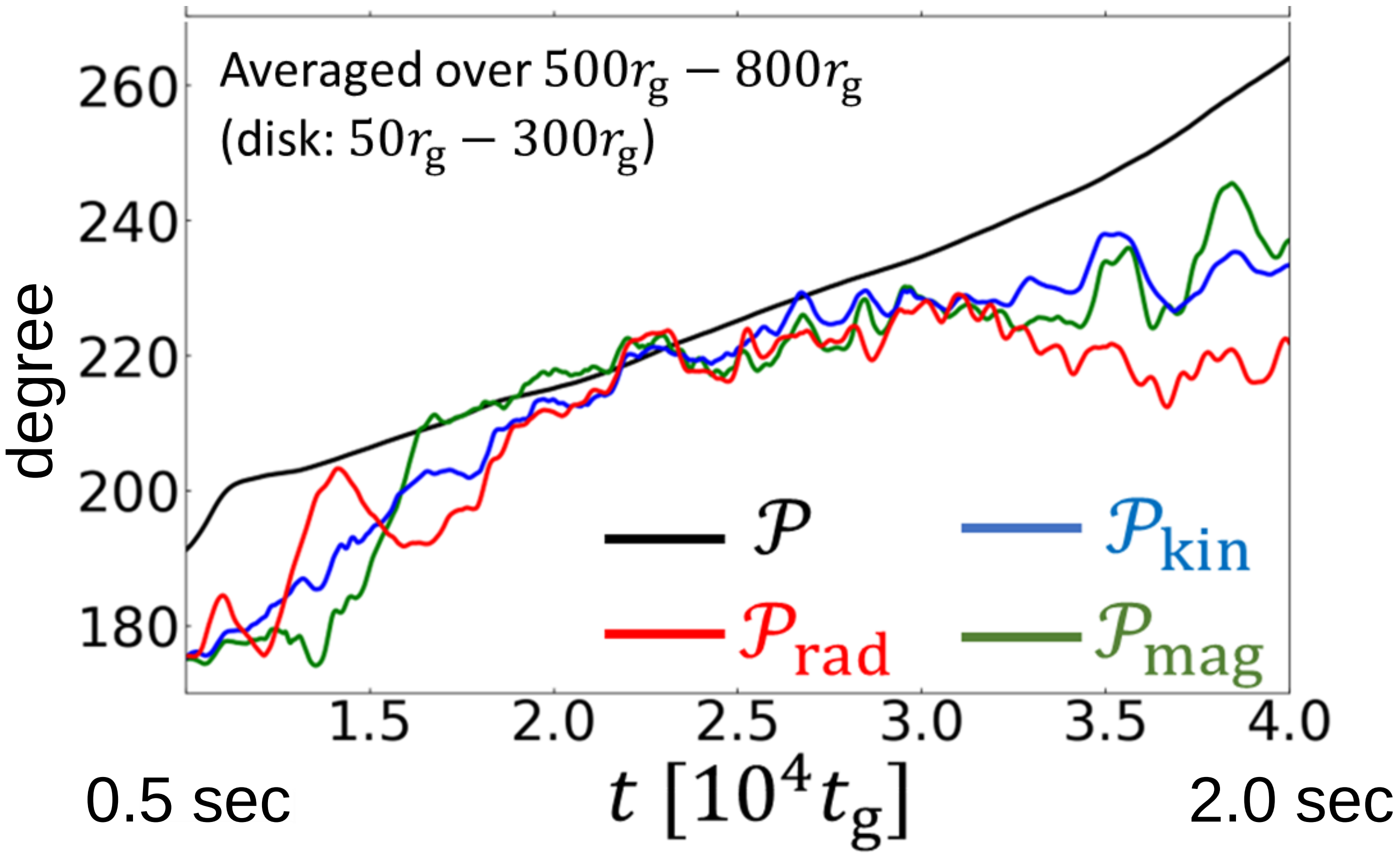
Disk Precession and Outflow formation



- GRRMHD simulation of the tilted supercritical accretion disk is performed by Asahina & Ohsuga (2024)
- Light blue shows the volume rendered density and orange shows the outflow with the velocity exceed 30% light speed
- Similar to previous studies, the jet ejects along the rotational axis of the accretion disk and precesses with the disk precession

Propagation Directions of Outflow and Radiation (Precession Angle)

$\mathcal{P}$: precession angle of the accretion disk
$\mathcal{P}_{\rm rad}$: precession angle of the radiation
$\mathcal{P}_{\rm kin}$: precession angle of the outflow
$\mathcal{P}_{\rm mag}$: precession angle of the magnetic flux



- The precession angles of disk, radiation, and outflow increase with time on average
- The changes of the precession angle of the radiation corresponds to the frequency of 74 mHz
- **The ejection directions of the outflow and radiation precess with the disk precession**

→Such precession could explain the QPOs with the frequency of about 0.1 Hz

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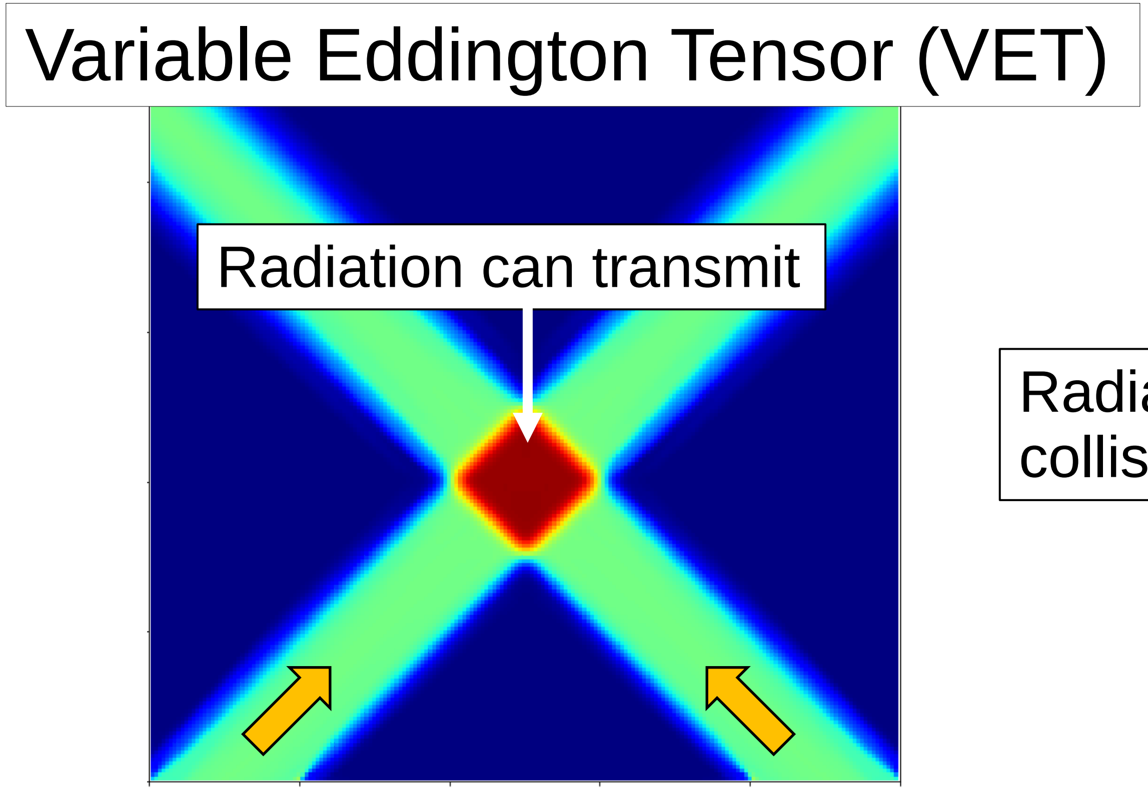
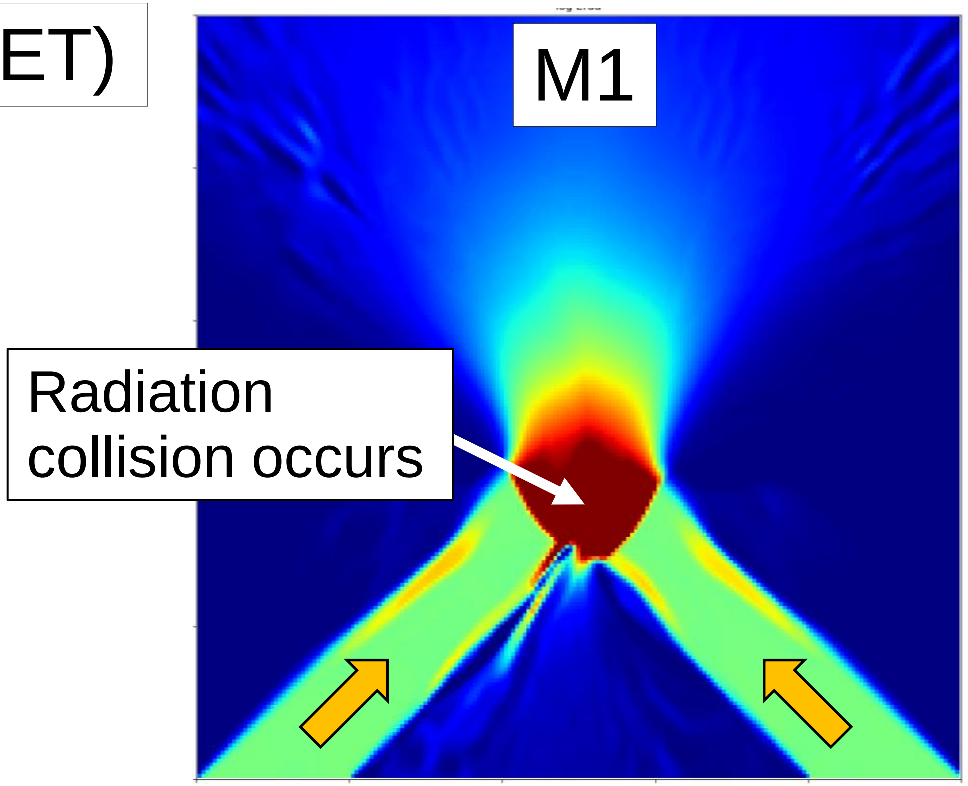
Unphysical Radiation Collision

Previous studies often adopt M1 method (the approximate method) for radiation transfer to save the calculation cost. The unphysical radiation collision occurs in the optically thin region.





Radiation energy density profiles for beam crossing problem

- VET method gives us exact solution but it is more expensive
- In VET simulation the radiation can transmit
- In M1 simulation, the radiation collides each other and beams are destroyed

Neural Network Model

In the previous study for Core-collapse Supernova simulation, the machine learning is useful for prediction of the Eddington tensor (Harada et al. 2022).

Recently, our group creates the machine learning model for BH accretion disks.

Input Data

Radiation energy density and radiation energy flux

F^i/E

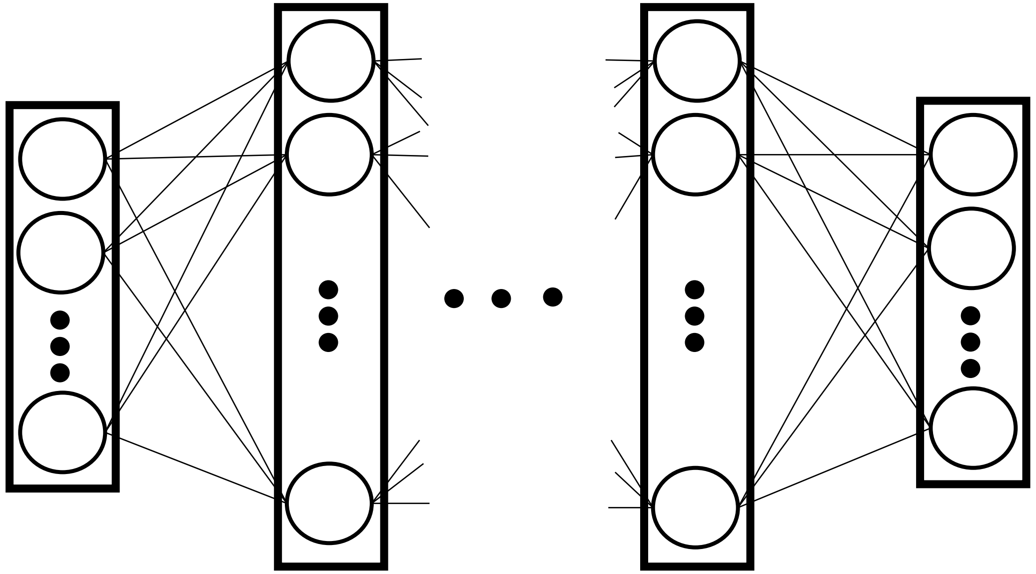
Gas density, gas pressure, velocity

ρ, p, u^i

(8 variables)

Hidden Layers

64 Neurons × 4Layers



Output Data

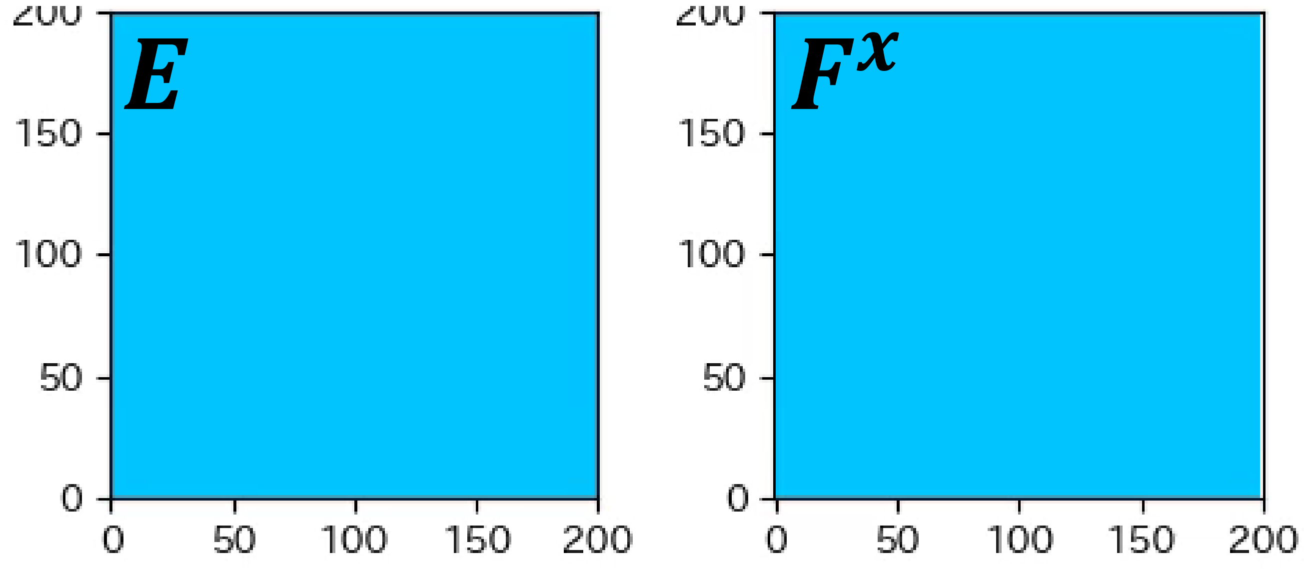
Eddington tensor (Index of anisotropy of radiation)

f^{ij}

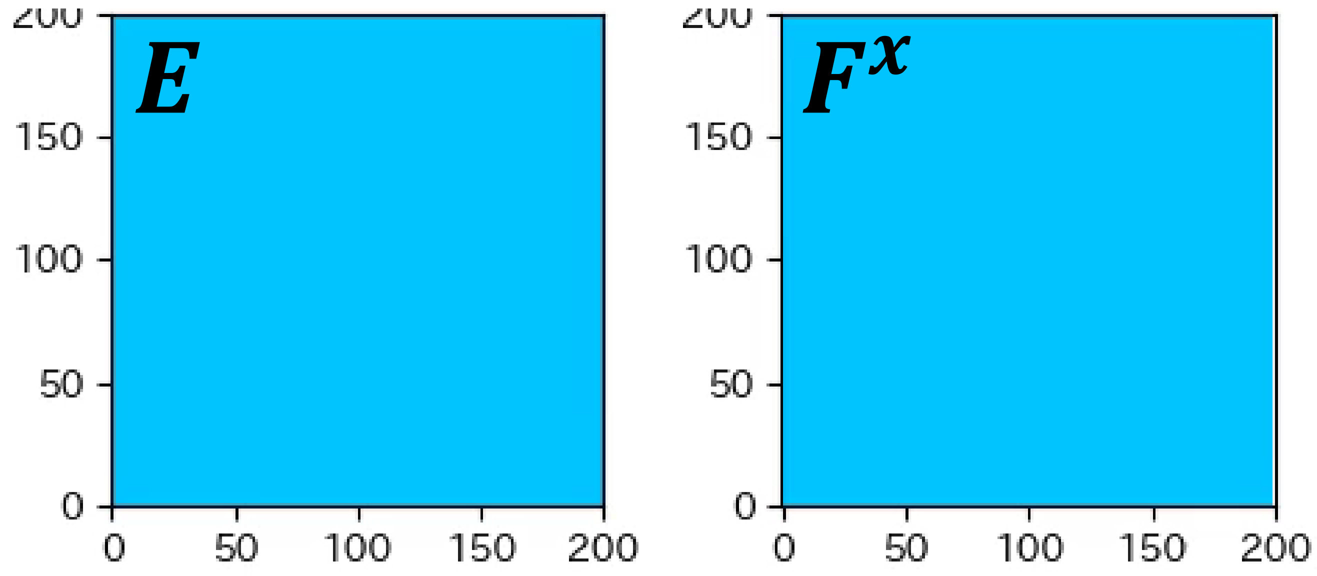
(6 variables)

Simulation with Neural Network (NN) Model

VET simulation
（Elapsed time：12 min）



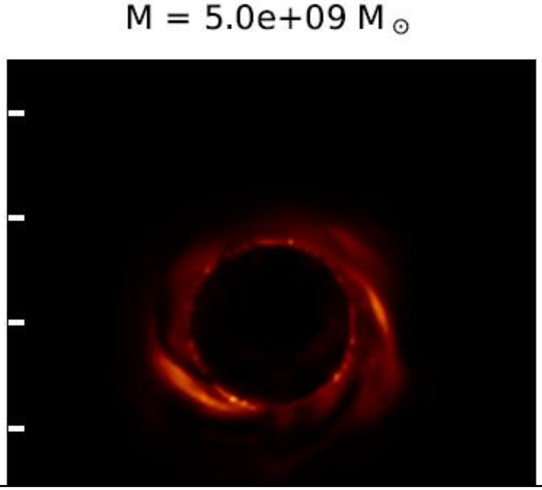
NN Simulation
（Elapsed time：3 min）



- Simulation with NN model can solve the beam crossing without unphysical radiation collision
- The elapsed time of the NN simulation becomes 4 times shorter than that of the VET simulation

Connection between Simulations and Observations by Machine Learning

Deep Horizon (Jeffrey et al. 2020): two convolutional deep neural networks that reproduce the physical parameters from the images of black hole shadows



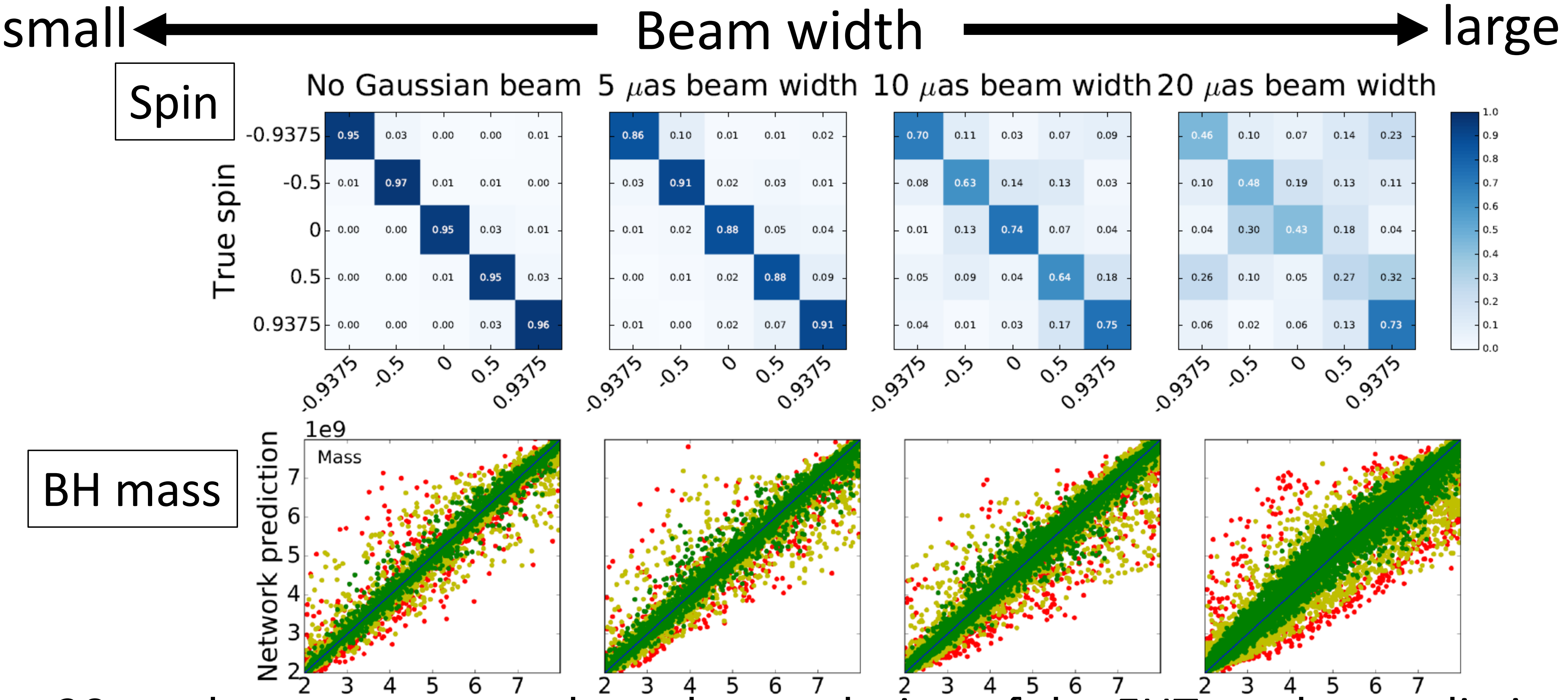
Input data (GRMHD simulations)

Parameter	Range
i	[15°, 25°]
$\dot{M}$	$[2 \times 10^{-6} M_\odot/yr, 0.01 M_\odot/yr]$
$R_{\rm high}$	[1, 100]
M	$[2 \times 10^9\ M_\odot, 8 \times 10^9\ M_\odot]$
PA	[0°, 360°]
a	0, ± 0.5, ± 0.9375

→ **Convolutional Neural Network** →

- Viewing angle i
- Mass accretion rate $\dot{M}$
- electron heating prescription $R_{\rm high}$
- BH mass M
- Position angle
- Spin parameter a

Dependence on Beam Width



The 20 μas beam corresponds to the resolution of the EHT, so the prediction accuracy for current observations is low. In the future higher resolution observations could enable the parameters of black holes to be predicted with better accuracy.

Summary

- I introduced the GRMHD and GRRMHD simulations of the BH accretion disks and application of machine learning
- Spinning black holes can be brighter and form stronger jet due to BZ mechanism
- Long time simulations of the tilt accretion disks will reveal the detail of the QPO in the future
- Machine learning can be a useful tool for speeding up simulations, increasing accuracy, and connecting simulations and observations