# ブラックホール（or 中性子星）降着流と噴出流
# の数値シミュレーション
# ～最近の成果と今後の発展～

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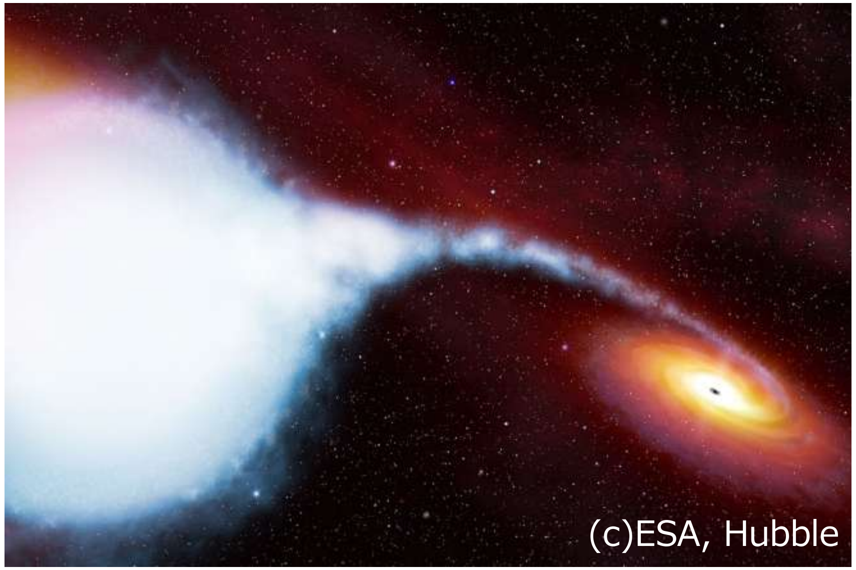
# Accretion Power

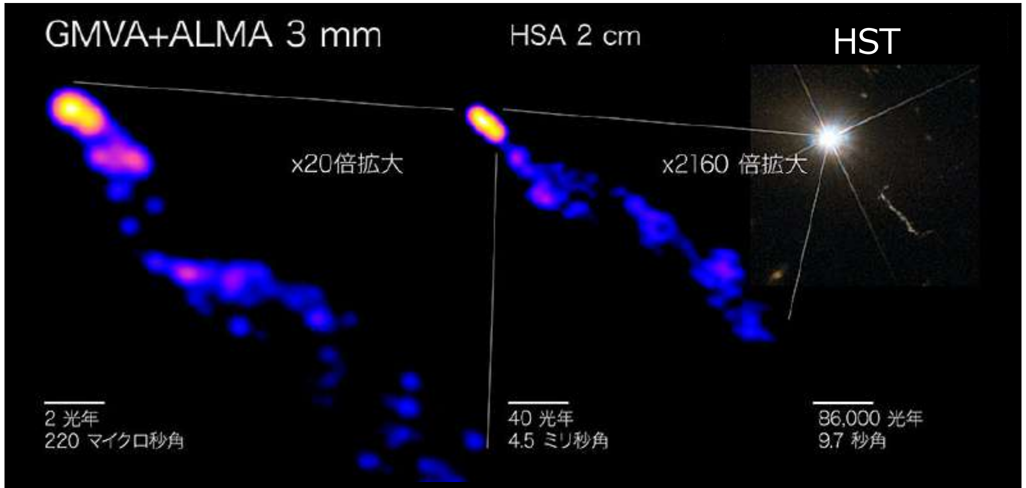
Black hole (BH) accretion system is one of the most powerful energy production mechanisms in the Universe. The luminous compact objects, like active galactic nuclei, X-ray binaries, Gamma-ray bursts, are believed to be powered by the BH accretion system.

X-ray binary (Cyg X-1)



(c)ESA, Hubble

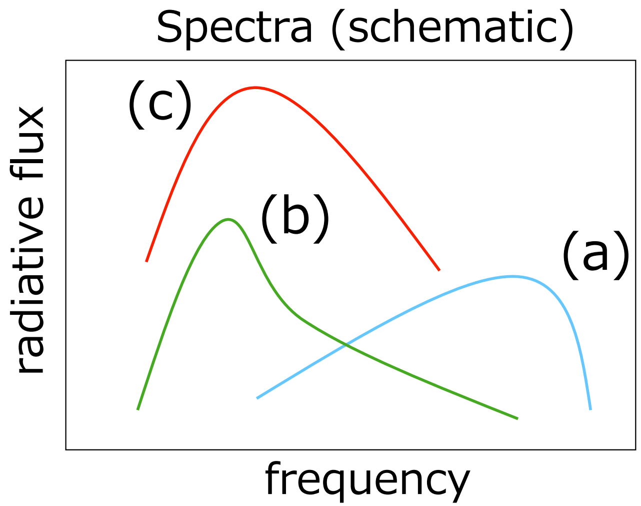
quasar (3C273)



(c)Hiroki Okino and Kazunori Akiyama; GMVA+ALMA and HSA images: Okino et al.; HST Image: ESA/Hubble & NASA

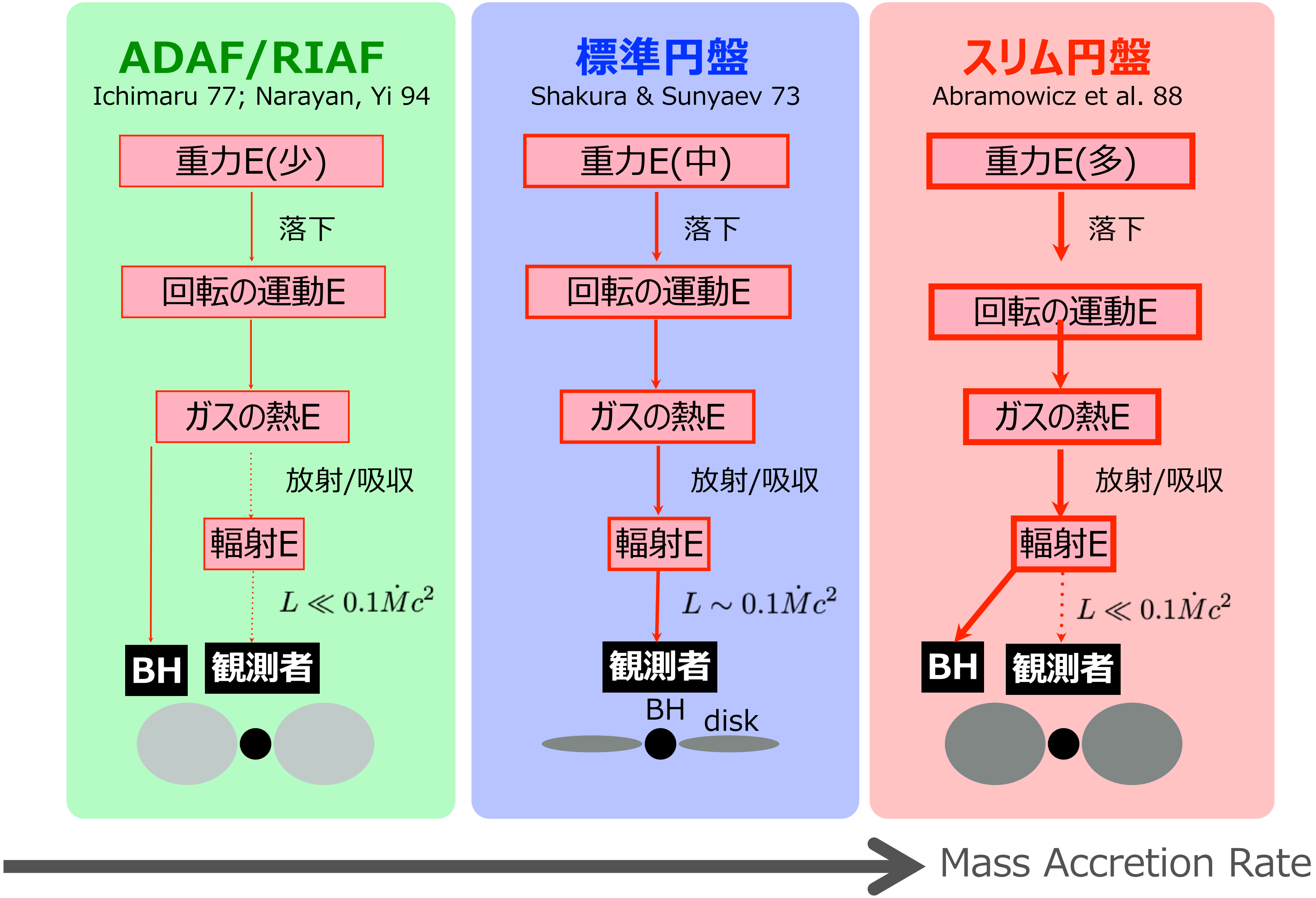
# Three Accretion Modes

Different spectral states imply the existence of different accretion modes



**Mass accretion rate (disk luminosity)** →

|  | (a) RIAF/ADAF | (b) Standard disk | (c) Slim disk |
|---|---|---|---|
| 温度（10Msun） | $\sim 10^{9\text{-}10}$K | $\sim 10^{7}$K | $\sim 10^{8}$K |
| 光学的厚み | 薄い | 厚い | 厚い |



## ADAF/RIAF

Ichimaru 77; Narayan, Yi 94

重力E(少)

落下

回転の運動E

ガスの熱E

放射/吸収

輻射E

$L \ll 0.1\dot{M}c^2$

**BH**

**観測者**

## 標準円盤

Shakura & Sunyaev 73

重力E(中)

落下

回転の運動E

ガスの熱E

放射/吸収

輻射E

$L \sim 0.1\dot{M}c^2$

**観測者**

BH disk

## スリム円盤

Abramowicz et al. 88

重力E(多)

落下

回転の運動E

ガスの熱E

放射/吸収

輻射E

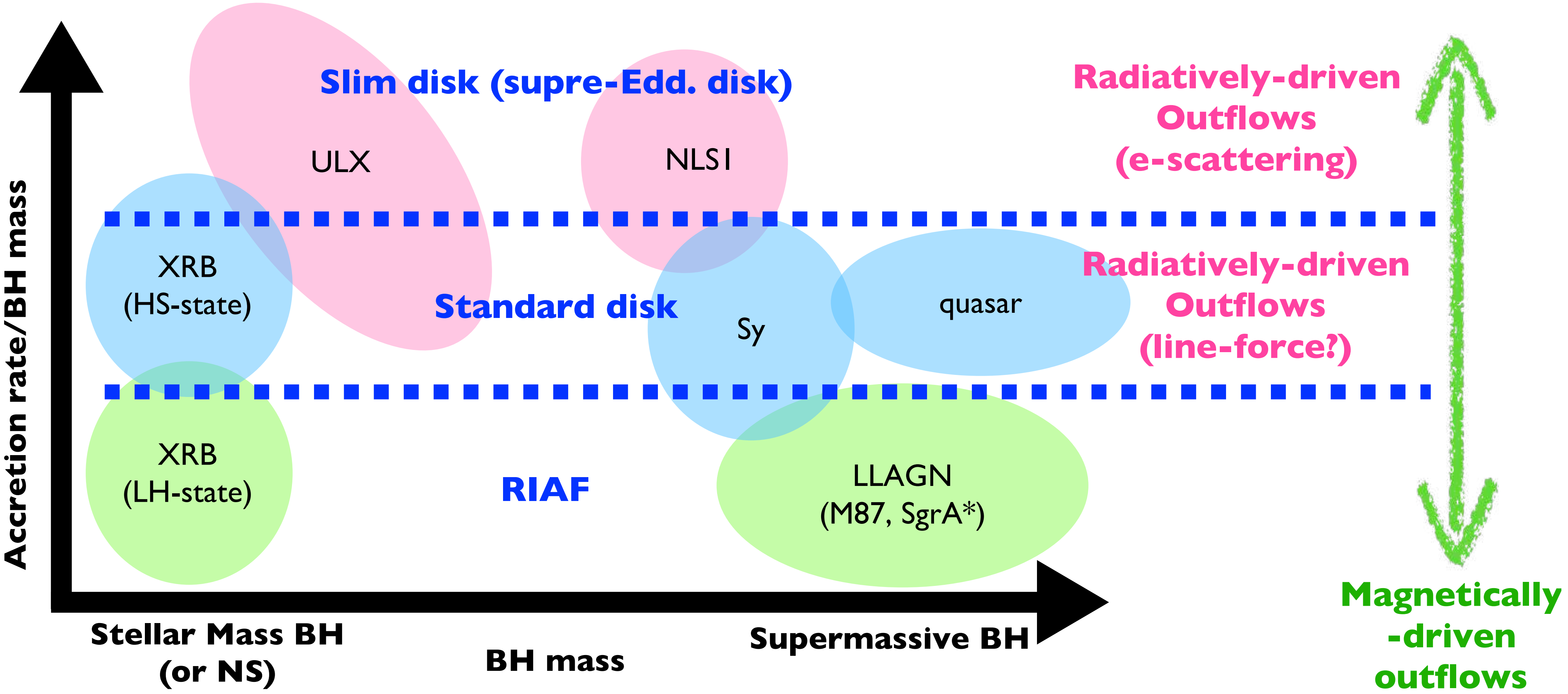
$L \ll 0.1\dot{M}c^2$

**BH**

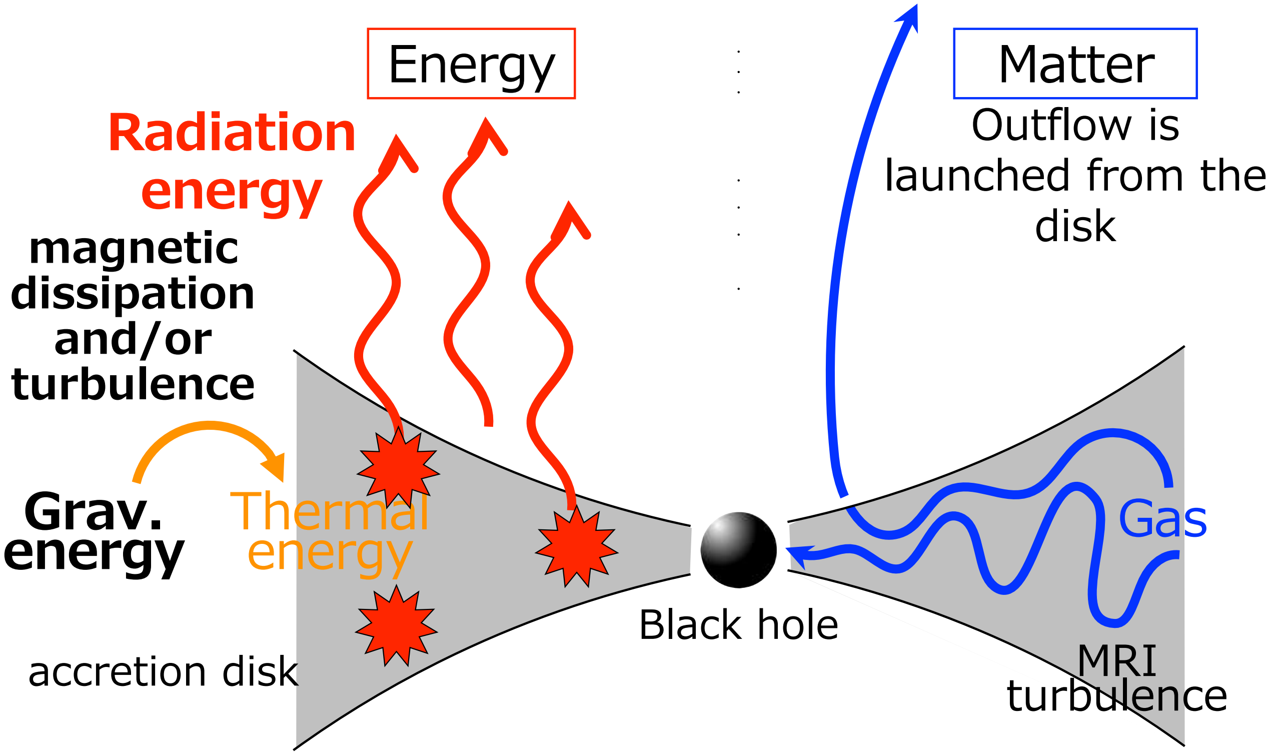
**観測者**

Mass Accretion Rate

# Three Accretion Modes



# Importance of Radiation and Magnetic Fields



Radiation-HD/MHD Simulations are necessary for high accretion rate.

**Magnet Fields;**

- Angular momentum is transported by MRI, leading to the mass accretion onto BHs.
- Magnetic dissipation heats the gas (heating)
- Magnetic force drives outflows

**Radiation Fields;**

- Disk loses the energy by emitting photons (cooling).
- Radiation pressure determines the thickness of the disk.
- Radiation force drives outflows

# Development of Simulations of Super-Edd. disks

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)

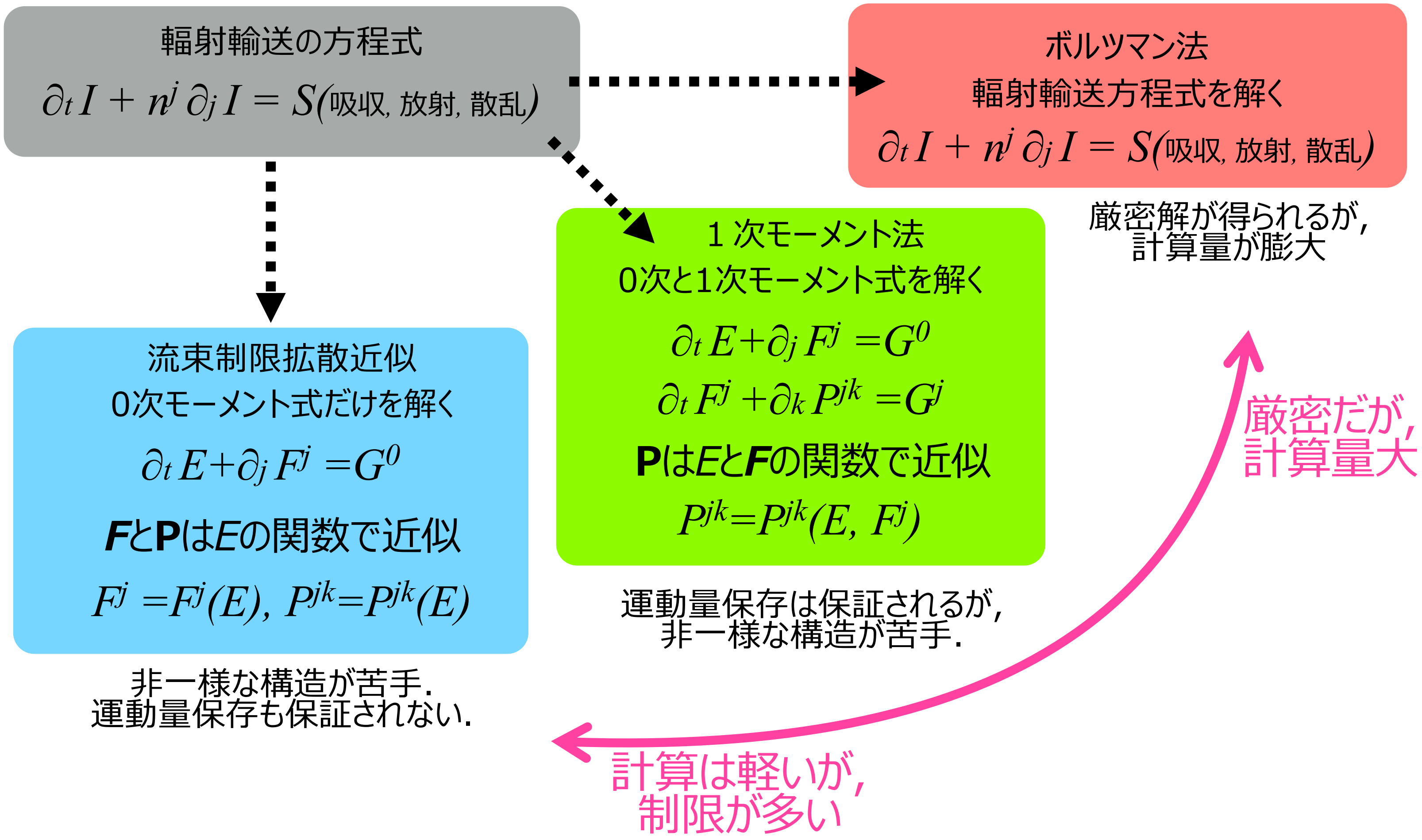
2014~

**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, Asahina et al. 2022**, Brandon 2023, **Asahina & Ohsuga submitted**).

# Numerical Methods for Radiation Field



輻射輸送の方程式

$\partial_t I + n^j \partial_j I = S($吸収, 放射, 散乱$)$

ボルツマン法

輻射輸送方程式を解く

$\partial_t I + n^j \partial_j I = S($吸収, 放射, 散乱$)$

厳密解が得られるが,
計算量が膨大

１次モーメント法

0次と1次モーメント式を解く

$$\partial_t E + \partial_j F^j = G^0$$

$$\partial_t F^j + \partial_k P^{jk} = G^j$$

**P**は*E*と***F***の関数で近似

$$P^{jk} = P^{jk}(E, F^j)$$

運動量保存は保証されるが,
非一様な構造が苦手.

流束制限拡散近似

0次モーメント式だけを解く

$$\partial_t E + \partial_j F^j = G^0$$

***F***と**P**は*E*の関数で近似

$$F^j = F^j(E),\ P^{jk} = P^{jk}(E)$$

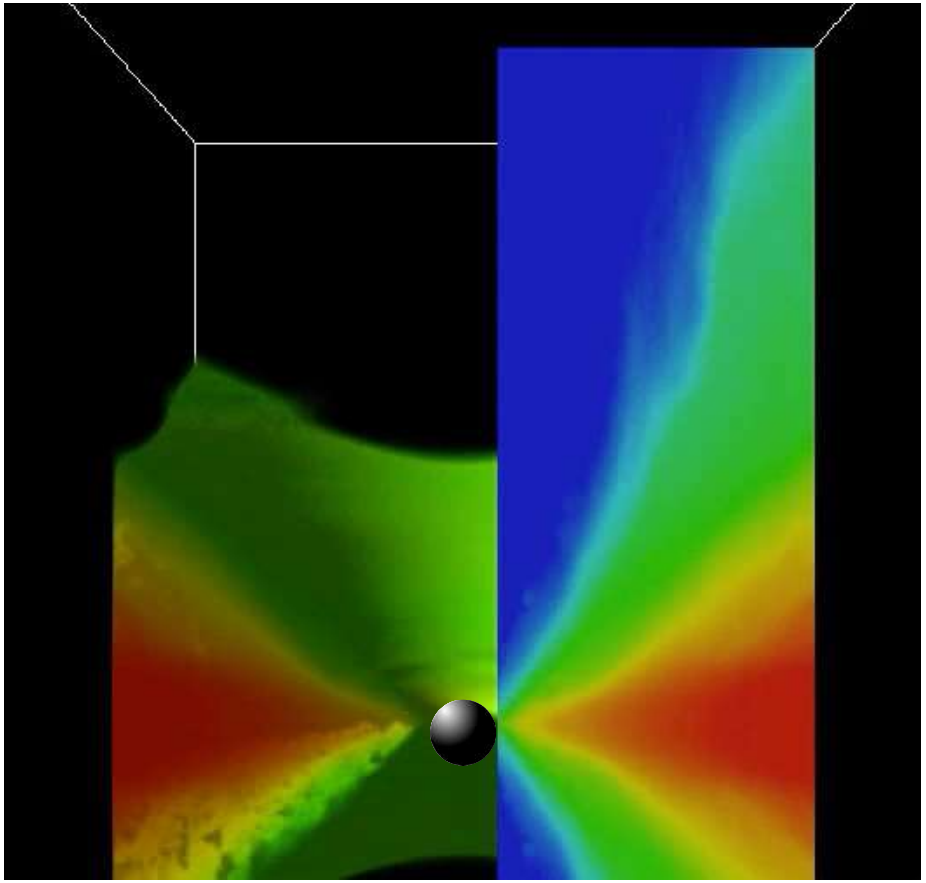
非一様な構造が苦手.
運動量保存も保証されない.

厳密だが,
計算量大

計算は軽いが,
制限が多い

# Radiation-MHD simulations Super-Edd. Flows

Ohsuga et al. 2009; Ohsuga & Mineshige 2011



**Setup**

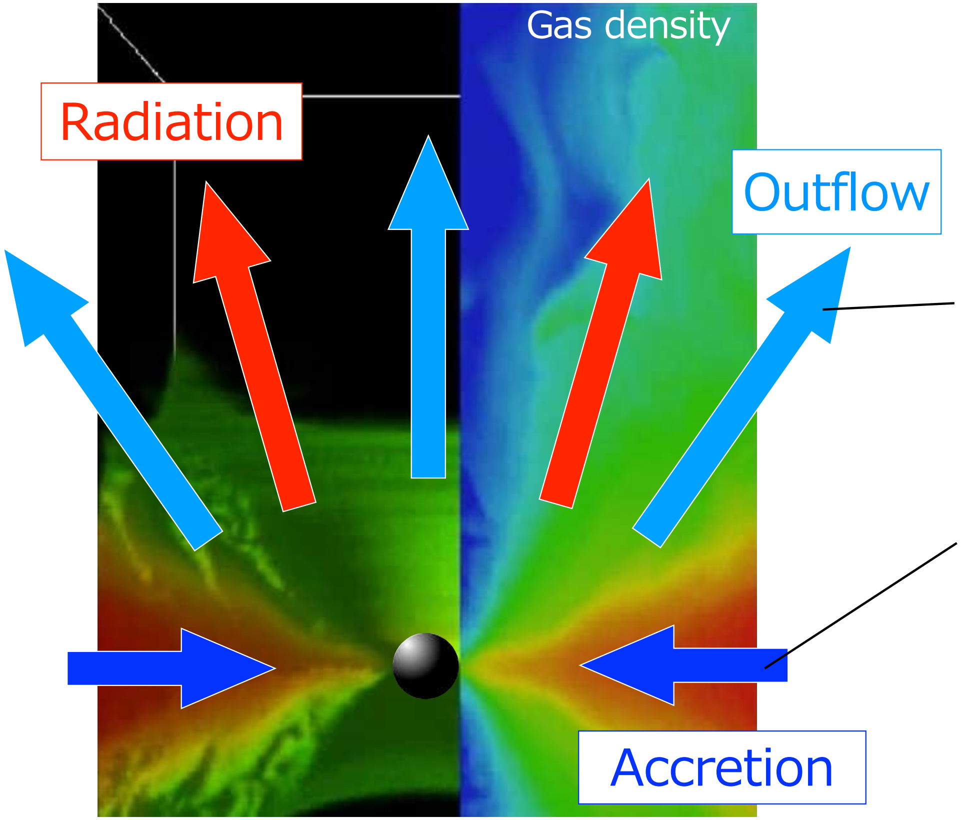
- BH mass: 10Msun
- Initial condition: equilibrium torus with embedded poloidal magnetic field (plasma-beta=100)

**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, Ohsuga 2007,
Jiang et al. 2014, 2019

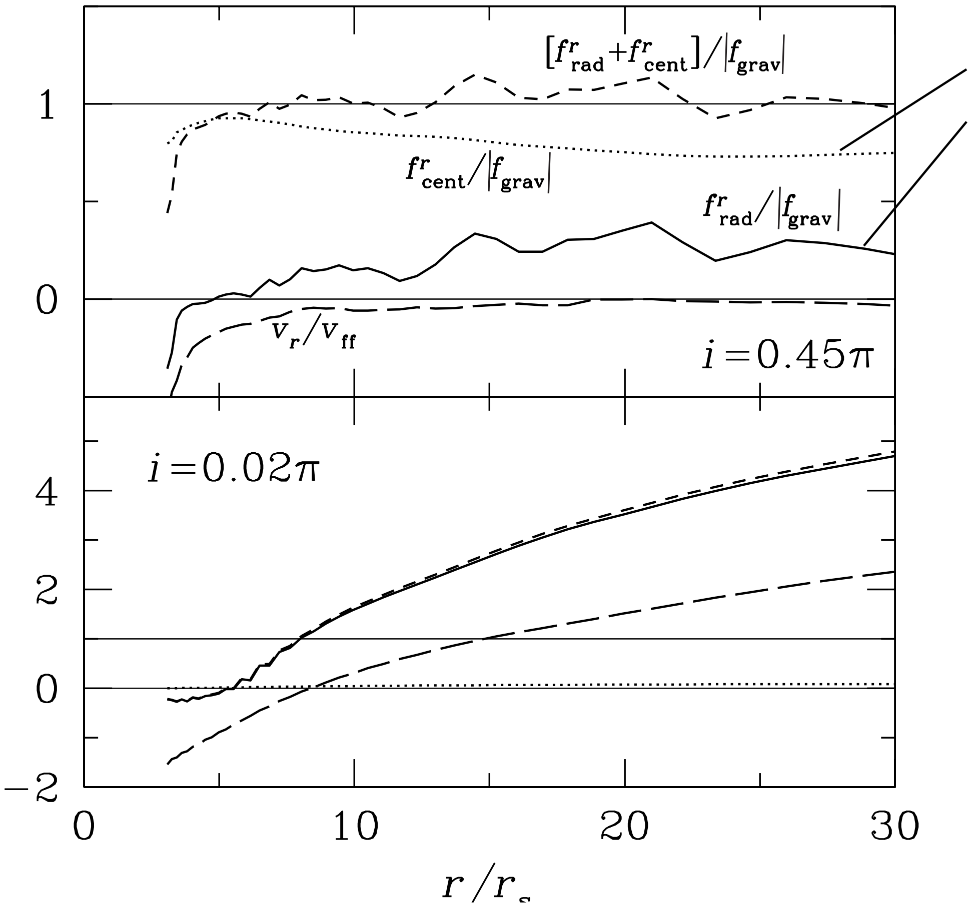
# Why is super-Eddington accretion feasible?



**Radiatively driven outflows:**
Strong radiation pressure supports the thick disk and generates the outflows above the disk.

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

# Why is super-Eddington accretion feasible?



遠心力/重力～70%
輻射力/重力～30%

$$\rho \frac{dv^a}{dt} = -\frac{\partial p_{\rm g}}{\partial x^a} + \frac{\rho\left(\kappa+\sigma\right)}{c}\tilde{F}^a$$

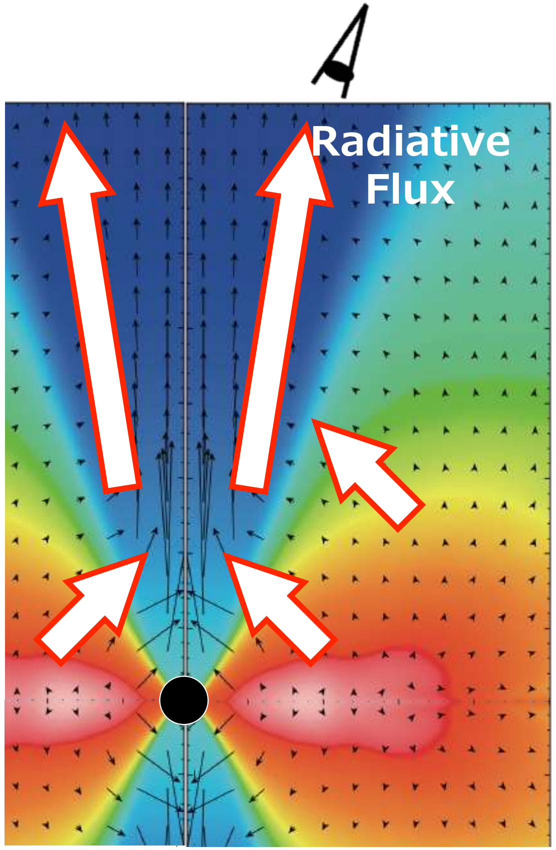
Optically thick

$$\cancel{\frac{1}{c}\frac{\partial \tilde{F}^b}{\partial t}} + c\frac{\partial \tilde{P}^{ab}}{\partial x^a} = -\rho\left(\kappa+\sigma\right)\tilde{F}^b$$

$$\tilde{P}^{ab} \to \tilde{E}\delta^{ab}/3$$

$$= -\frac{\partial}{\partial x^a}\left(p_{\rm g} + \frac{\tilde{E}}{3}\right)$$

# Apparent Luminosity



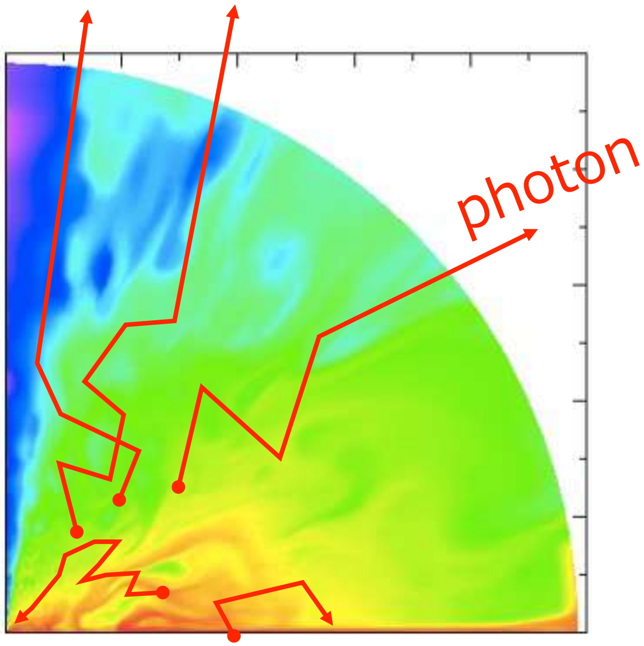
Ohsuga, Mineshige 2011

- 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 $\dot{M} \sim 100L_{Edd}/c^2$ & $L_{disk} \sim 3L_{Edd}$.

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

# Comparison with ULXs

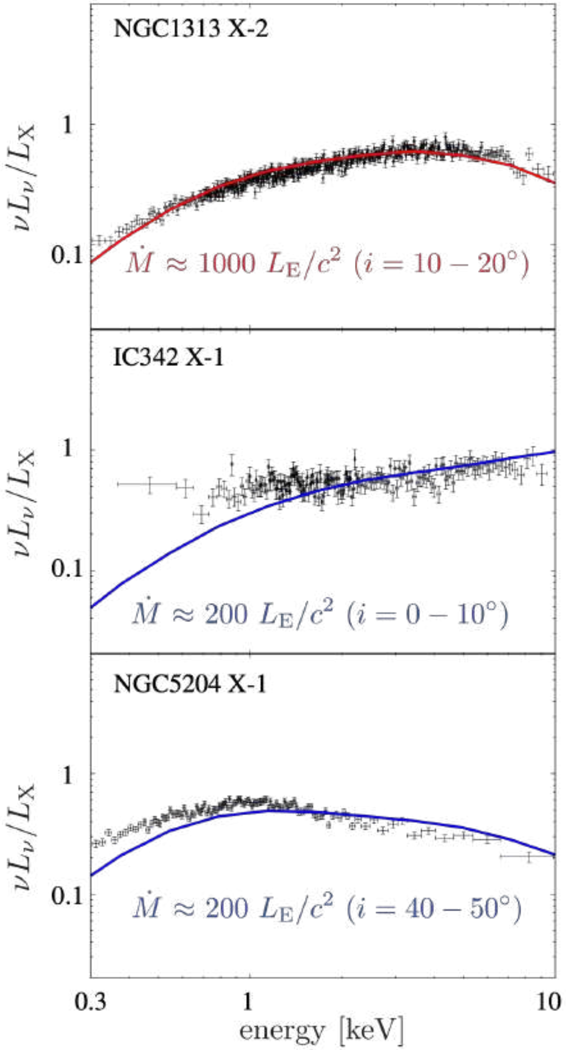


Monte Carlo
Radiation Transfer:

Simulated spectra nicely fit
the observations of ULXs.

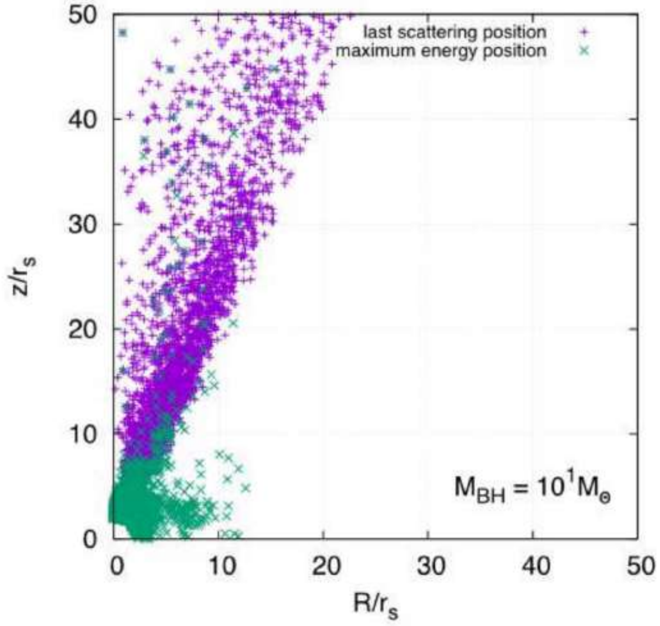
川島朋尚さん（東大宇宙線研）

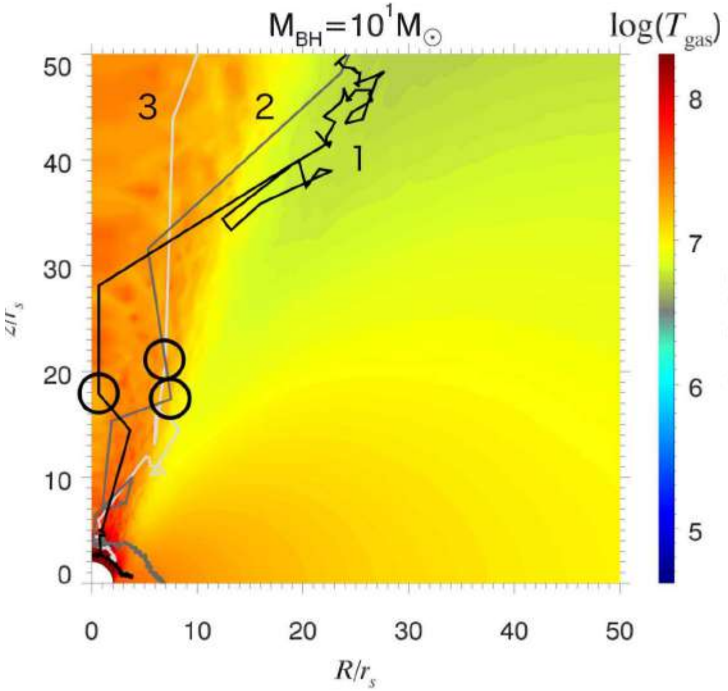
Kawashima et al. 2012
(data; Gladstone 2009)

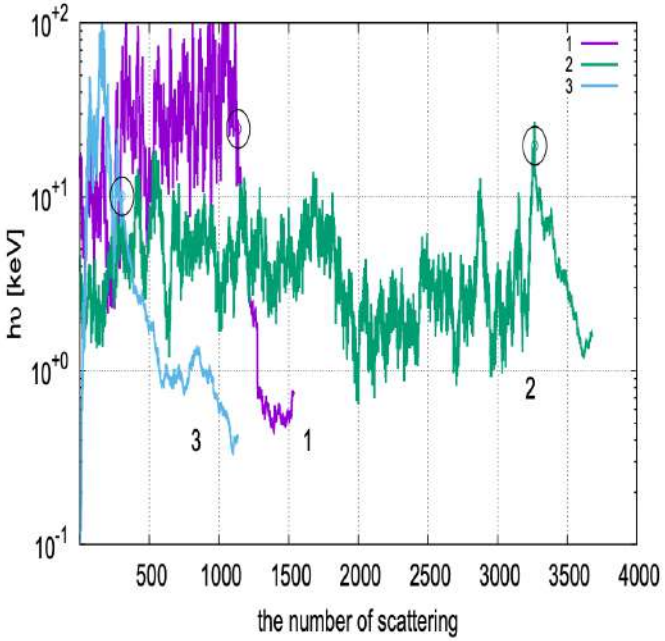


# Comparison with ULXs

Kitaki et al. 2017



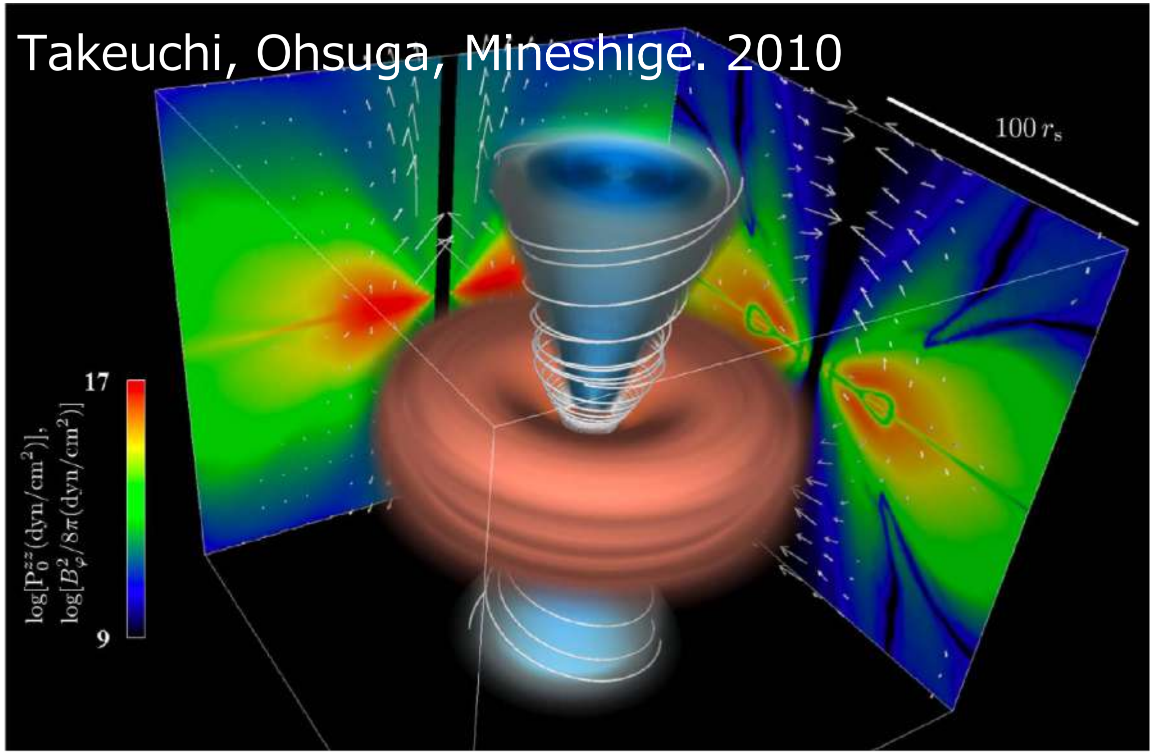




High-energy X-ray photons are generated within the funnel region. Photons undergo down-scattering above the disk, and in some cases, they are absorbed.

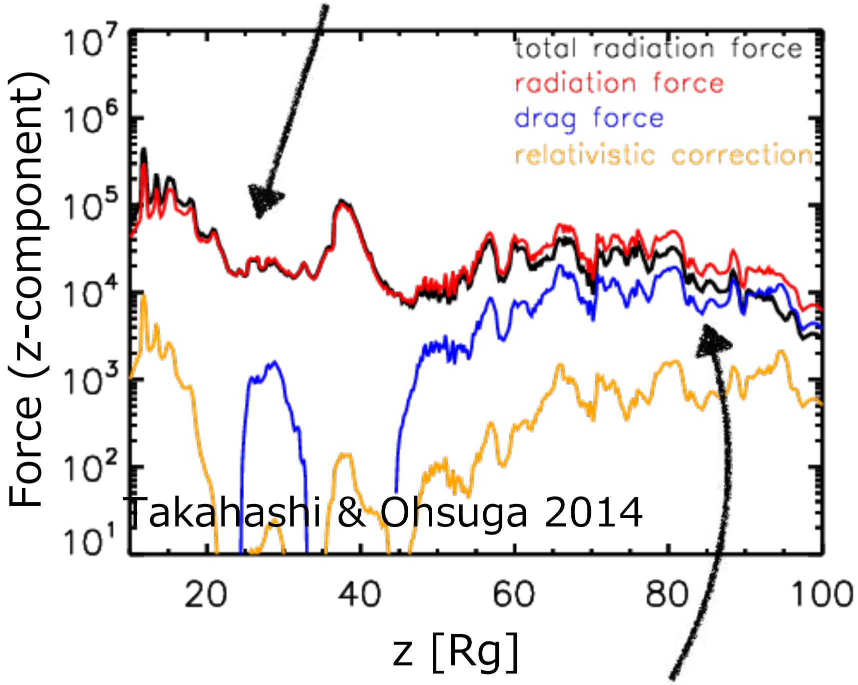
# Radiatively-driven Jets

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



Takeuchi, Ohsuga, Mineshige. 2010

Acceleration via
Radiation Flux Force

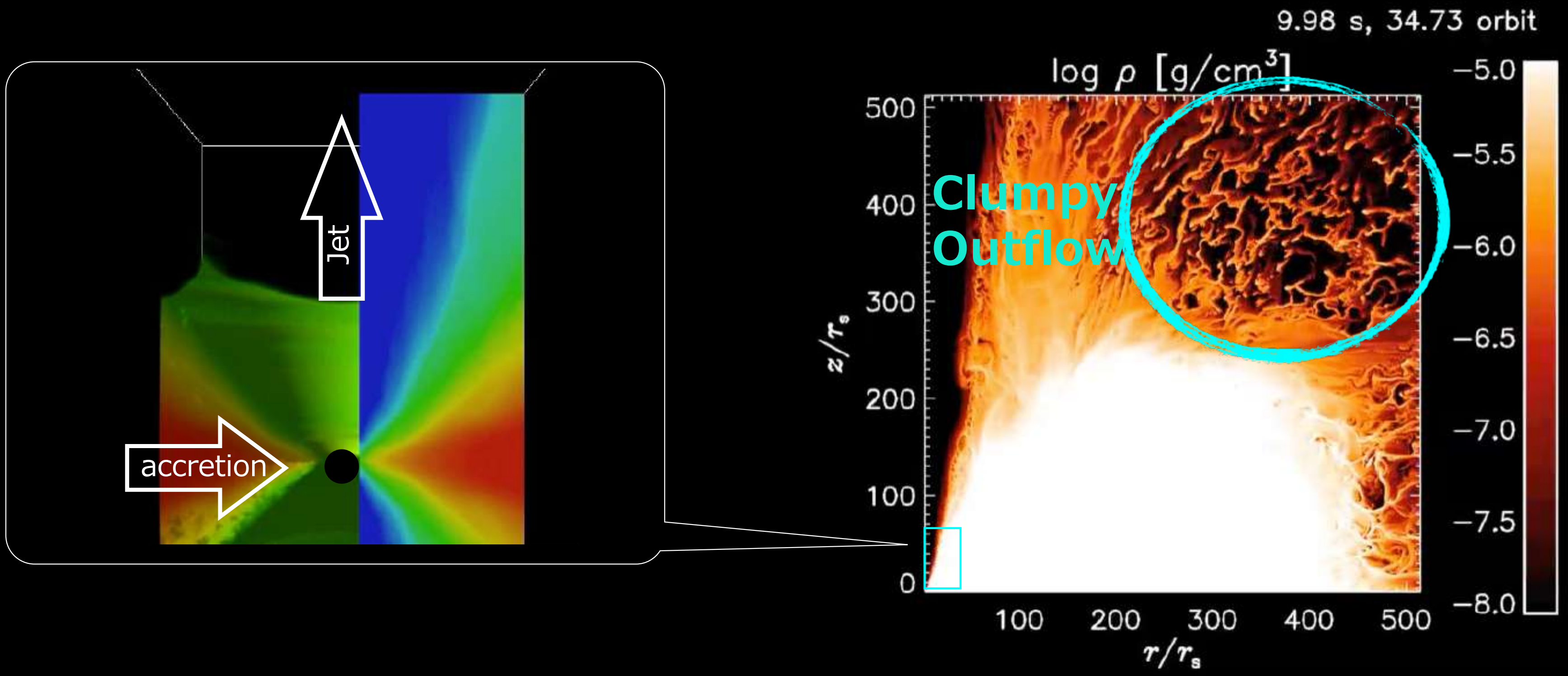


Takahashi & Ohsuga 2014

No acceleration because of
Flux Force ~ Drag Force

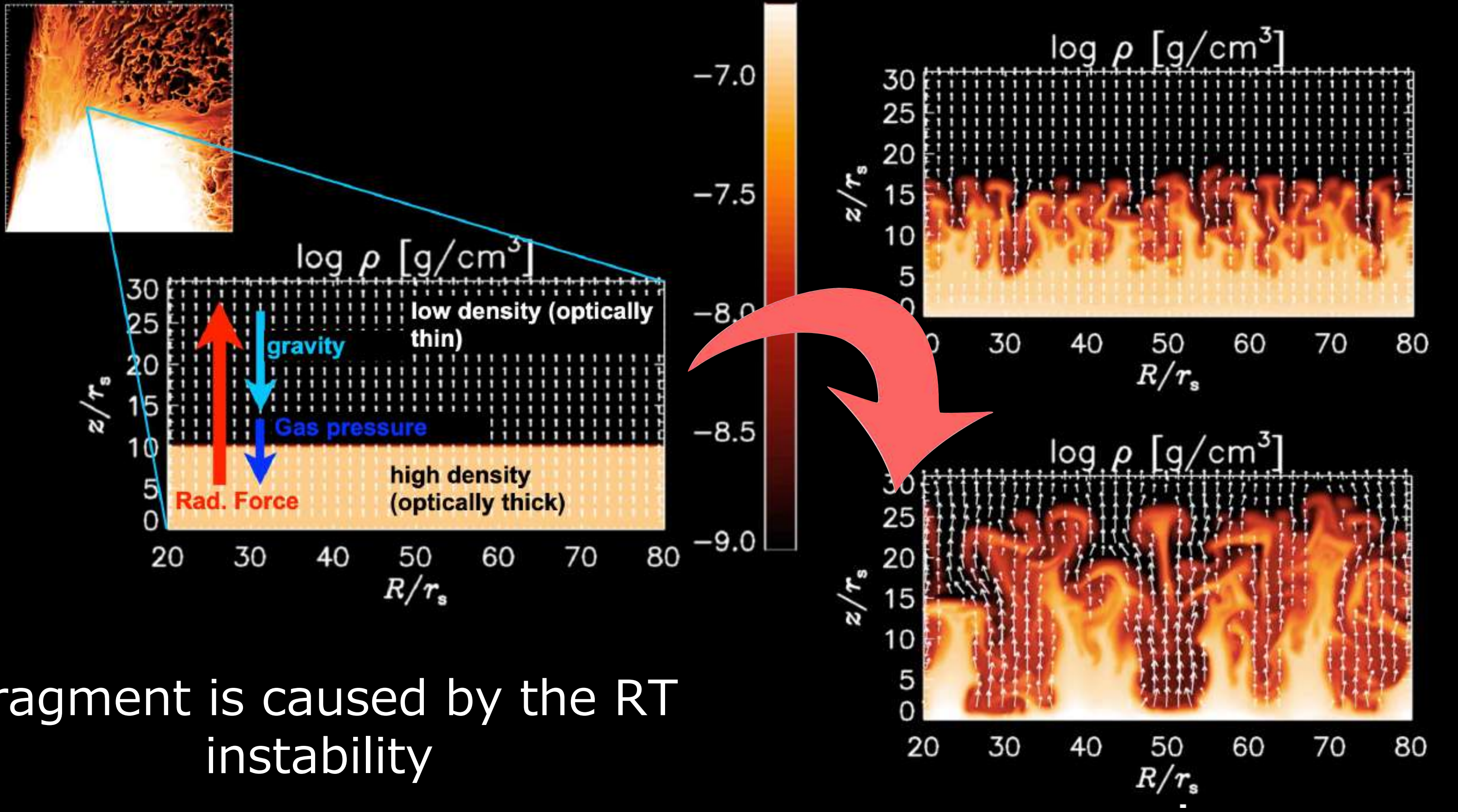
# Clumpy Outflows

Takeuchi, Ohsuga, Mineshige 2013



Clumpy outflows: Radiative Winds fragment into many gas clouds

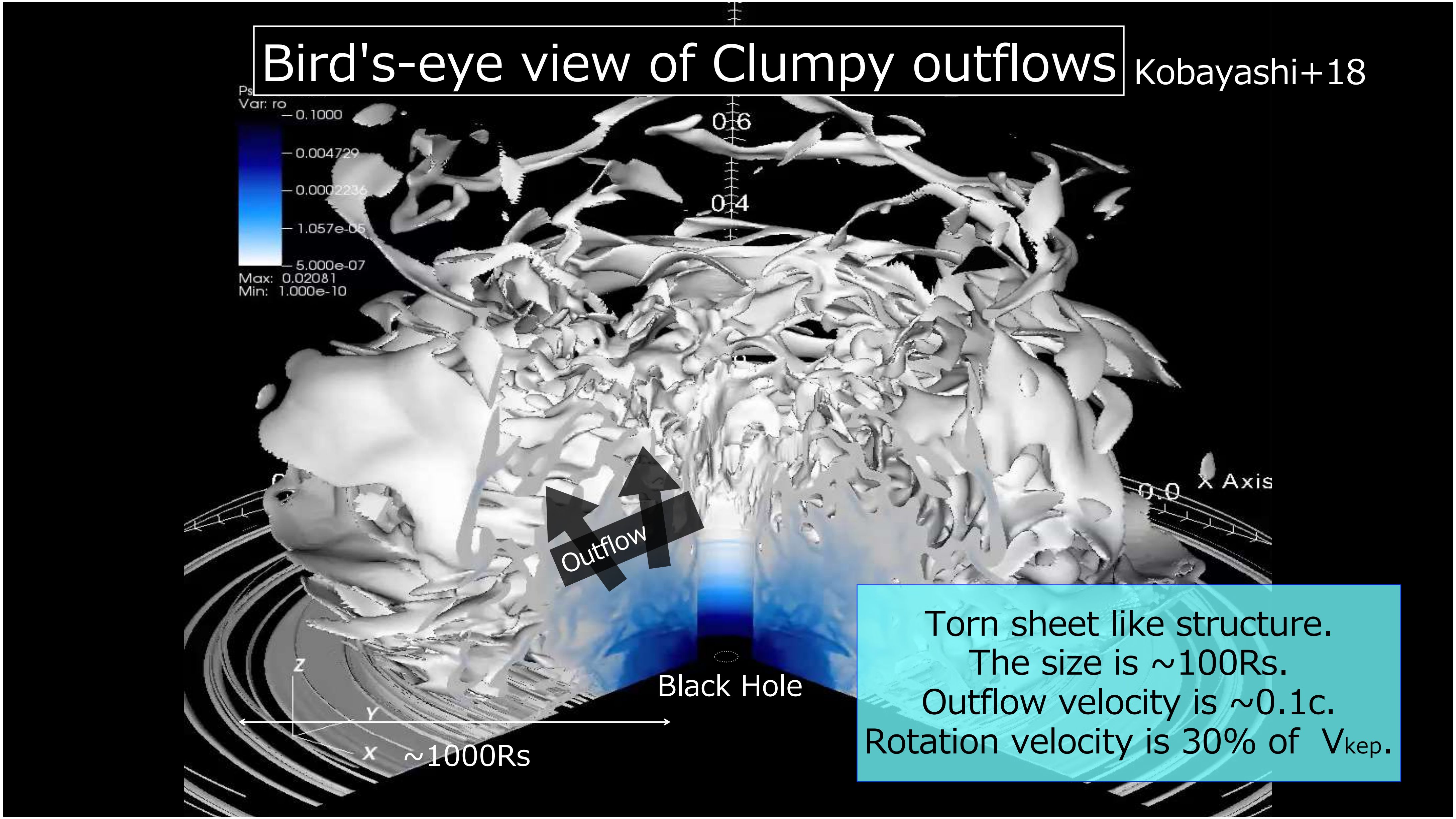
# RT instability



Fragment is caused by the RT instability

# Bird's-eye view of Clumpy outflows

Kobayashi+18

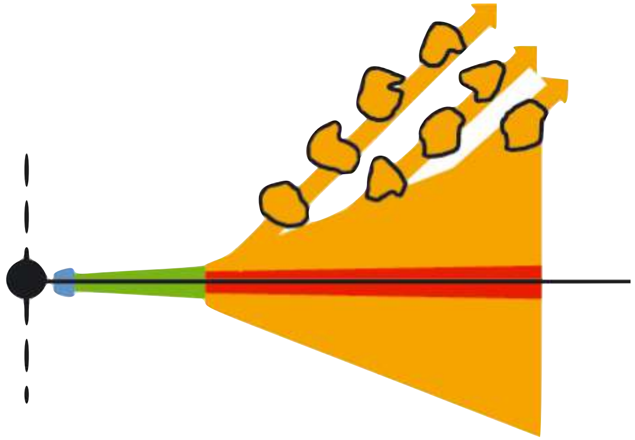


Torn sheet like structure.
The size is ~100Rs.
Outflow velocity is ~0.1c.
Rotation velocity is 30% of $V_{kep}$.

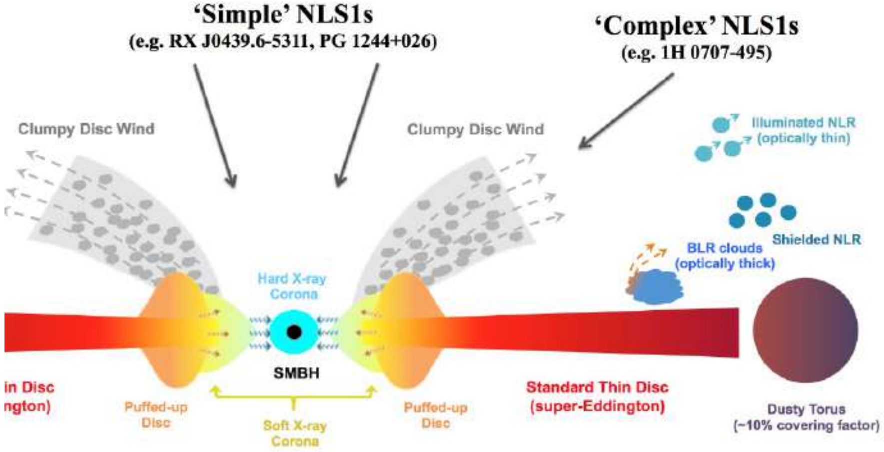
# Observations of Clumpy outflows

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

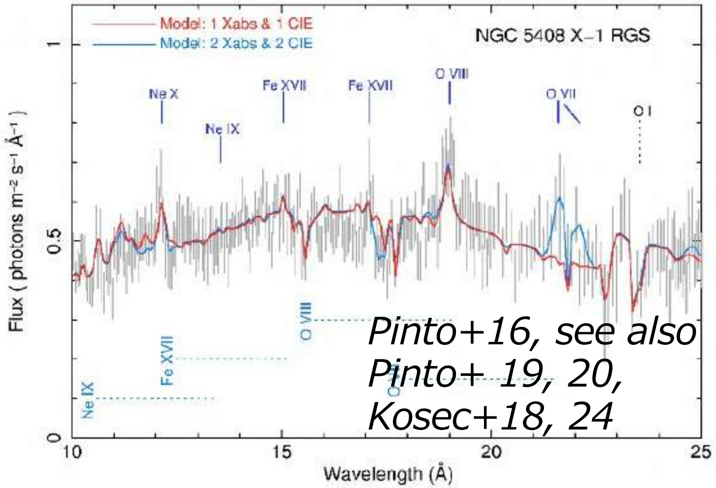


Jin+17 see also Motta+17

# Comparison with ULXs

<u>Absorption lines</u>

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



*Pinto+16, see also Pinto+ 19, 20, Kosec+18, 24*

<u>Time variation</u>

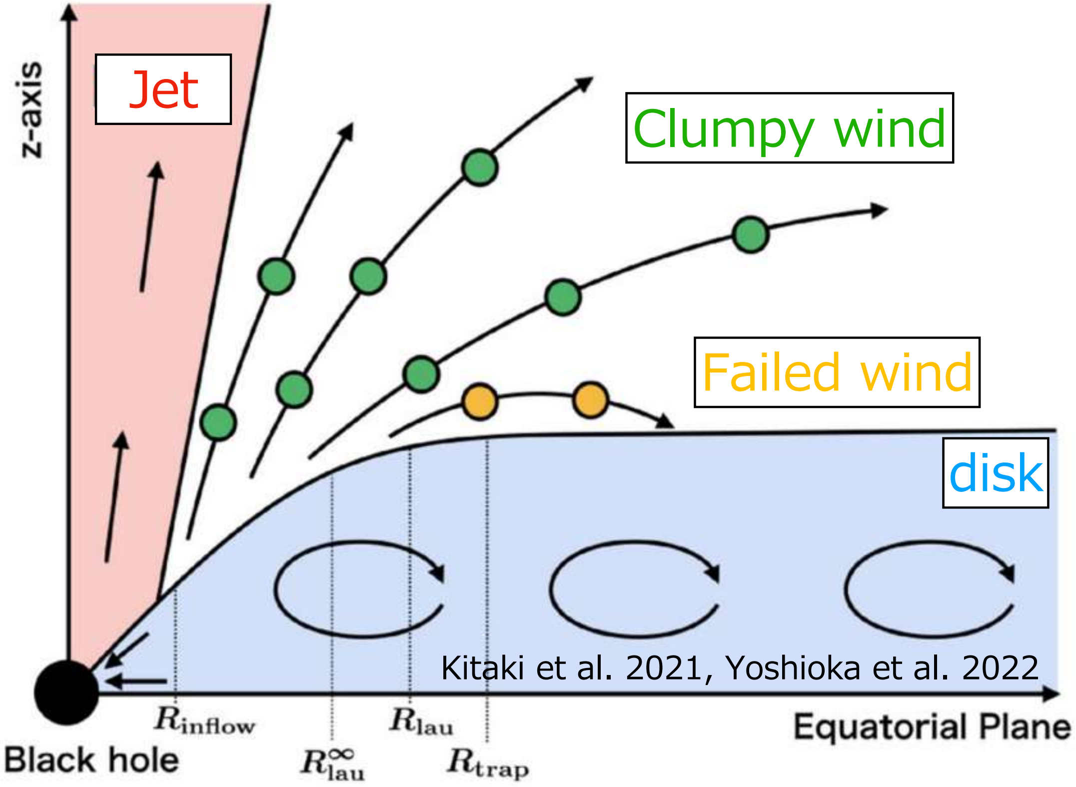
Timescale of the luminosity variation (100Rs/0.3V$_{\rm kep}$) is

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

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

# Overall structure of the super-Edd. flows

Schematic picture of the overall structure



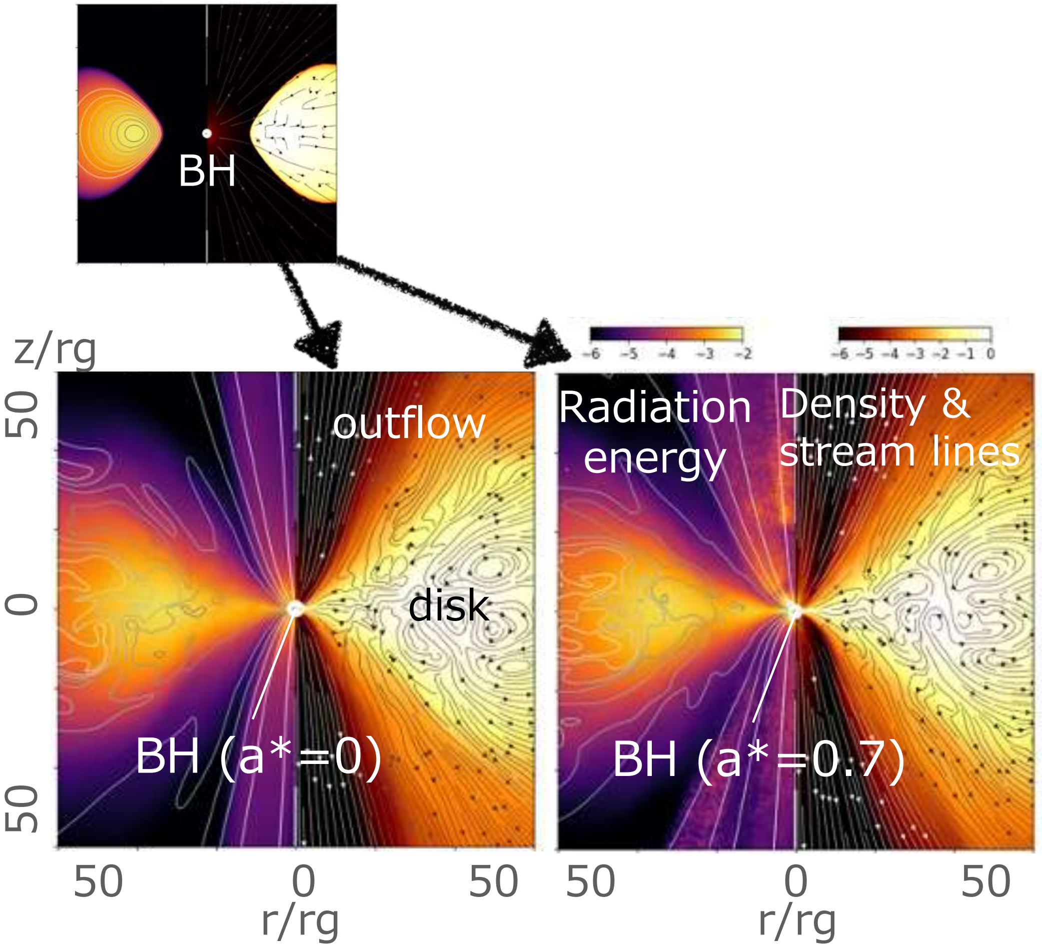
Kitaki et al. 2021, Yoshioka et al. 2022

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 (& failed wind).

# General Relativistic Radiation-MHD sim.

Utsumi, Ohsuga et al. 2022



**Setup**

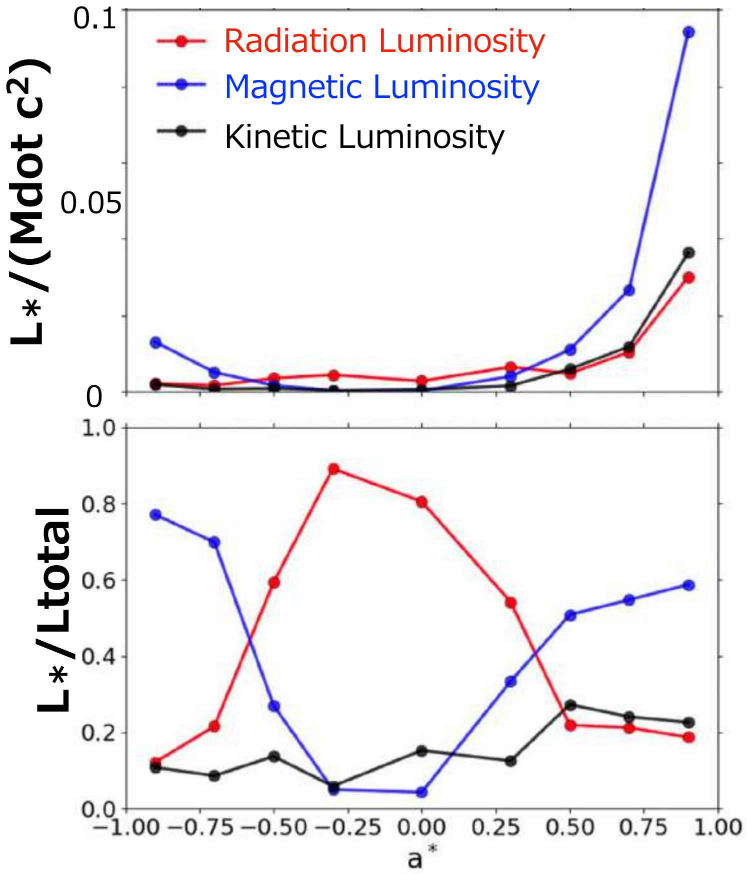
- BH mass: 10Msun
- Initial condition: equilibrium torus with embedded poloidal magnetic field (plasma-beta=100)
- Spin parameter: -0.9, -0.7, -0.5, -0.3, 0, 0.3, 0.5, 0.7, 0.9

**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

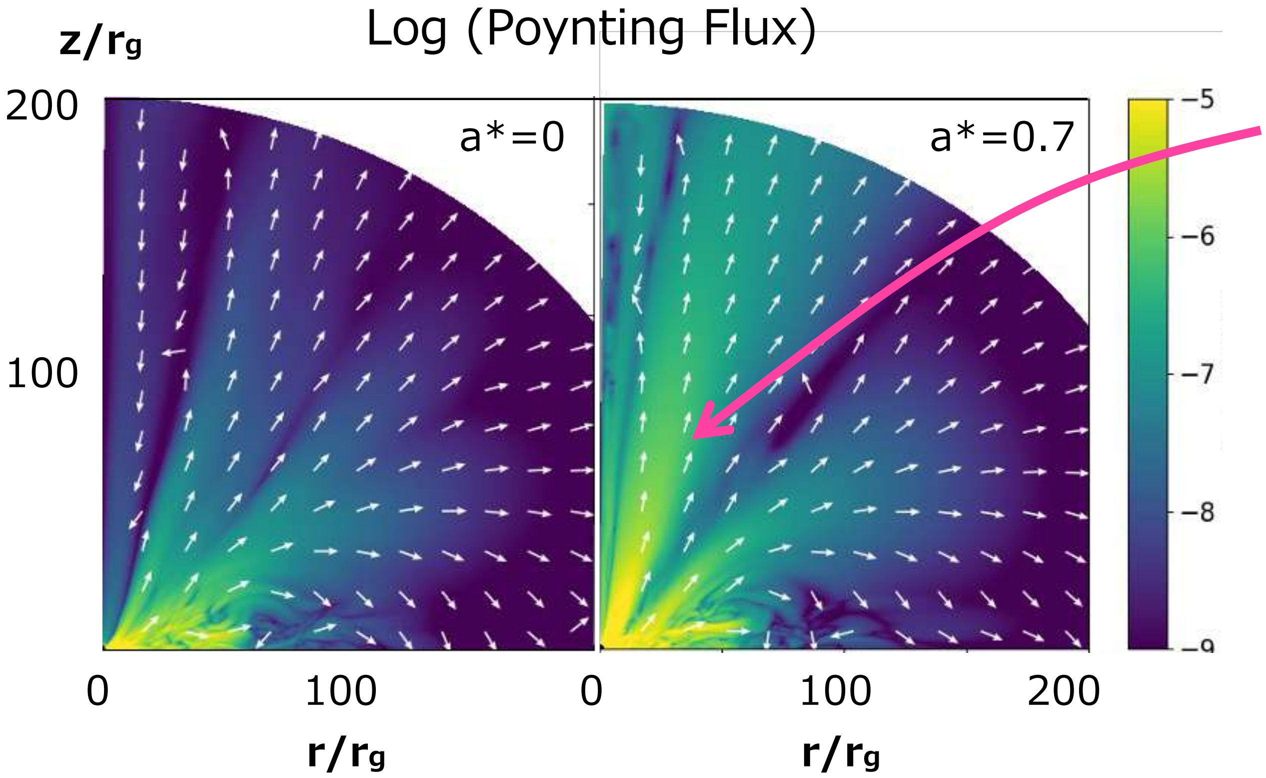


For the case of a*~0, energy is mainly released by the radiation. When |a*| is large, the energy released by the Poynting flux (Magnetic Luminosity) exceeds the Radiation Luminosity.

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.

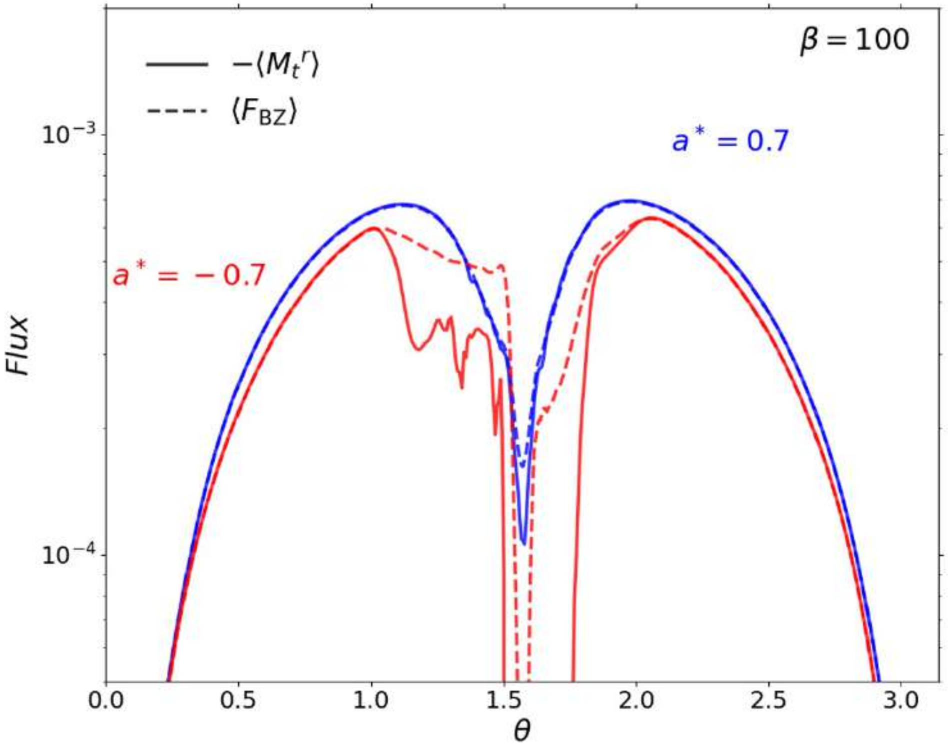
See also Sadowski et al 2014, 2019, Bandon 2023

# 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.

# Enhancement of Poynting Flux



実線：磁気フラックス

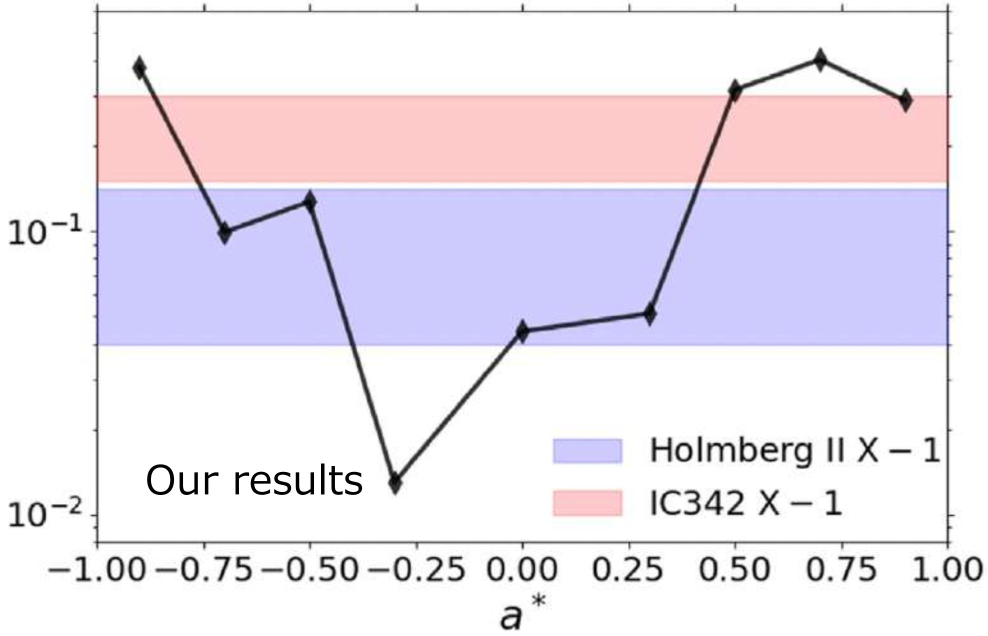
$$-M_t^r = -(b^2 u_t u^r - b_t b^r)$$

破線：BZフラックス

$$F_{\rm BZ}|_{r_{\rm H}} = 2(B^r)^2 \omega r_{\rm H}(\Omega_{\rm H} - \omega)\sin^2\theta$$

# Kinetic luminosity vs X-ray luminosity

Kinetic Luminosity/Isotropic X-ray Luminosity



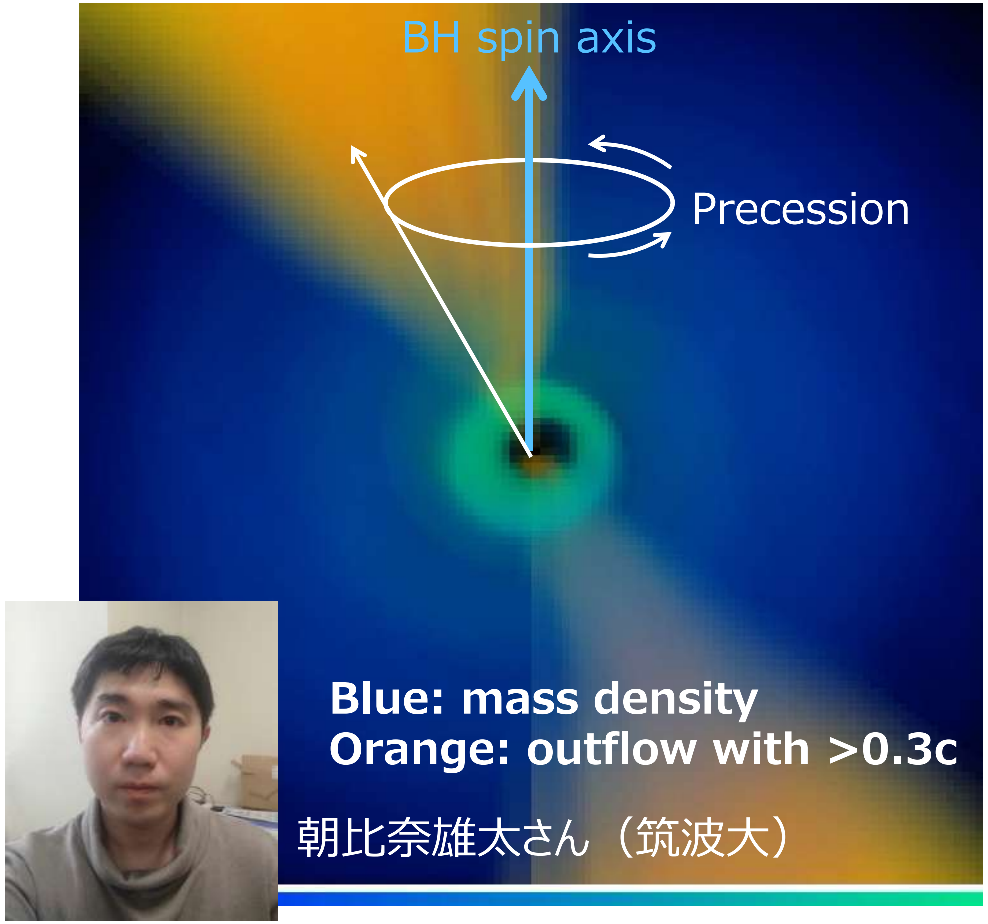
*Isotropic X-rau Luminosity:
Radiation luminosity observed
by face-on observer.

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 accepted yesterday



**Blue: mass density**
**Orange: outflow with >0.3c**

朝比奈雄太さん（筑波大）

## Setup

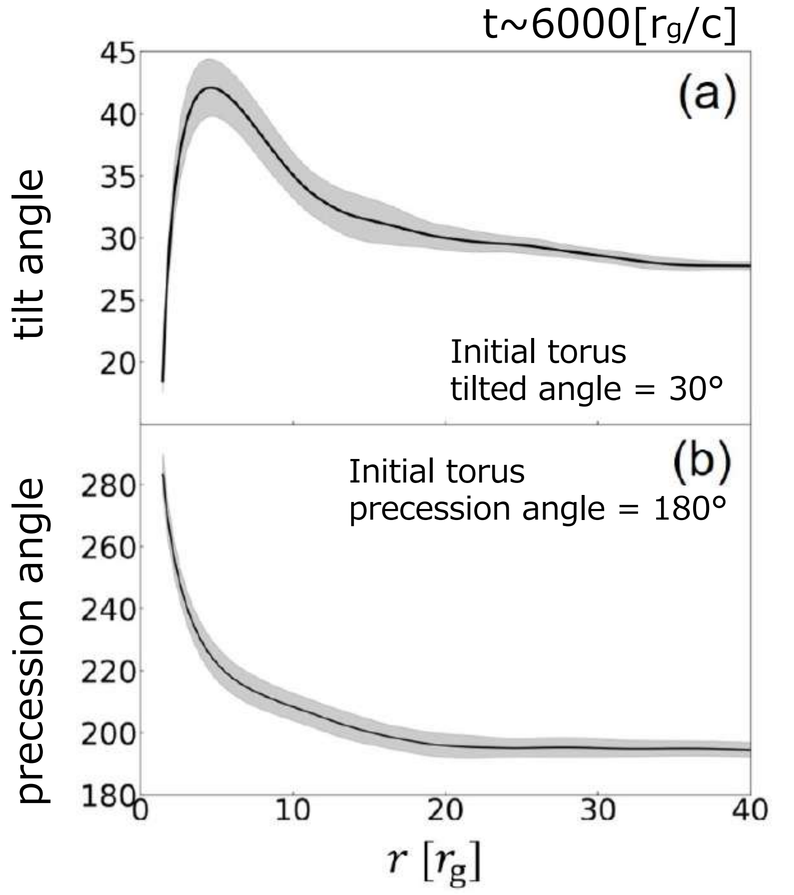
- BH mass: 10Msun
- Initial condition: equilibrium torus with embedded poloidal magnetic field (plasma-beta=100) tilted **30 degree**.
- Spin parameter: **0.9**

## Inflow-outflow structure

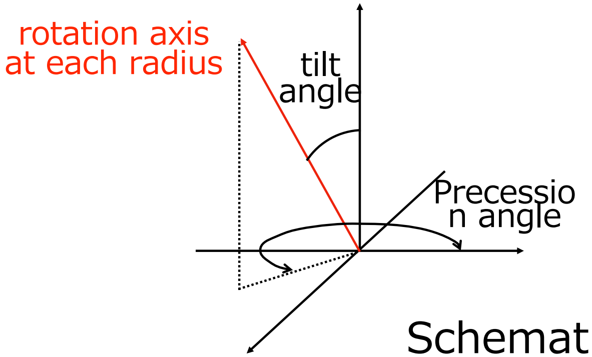
- The super-Eddington disk, which is tilted and twisted, forms.
- Strong outflows are also formed.

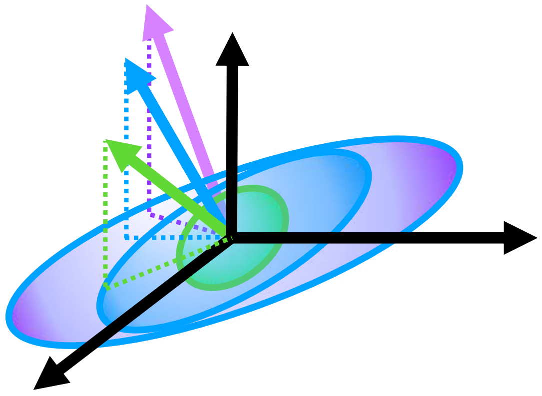
☐ Accretion rate: several **100** $\mathbf{L_{Edd}/c^2}$
☐ Radiation Luminosity: **several** $\mathbf{L_{Edd}}$
☐ Kinetic Luminosity: **several** $\mathbf{L_{Edd}}$

# Tilted and twisted super-Edd. disk



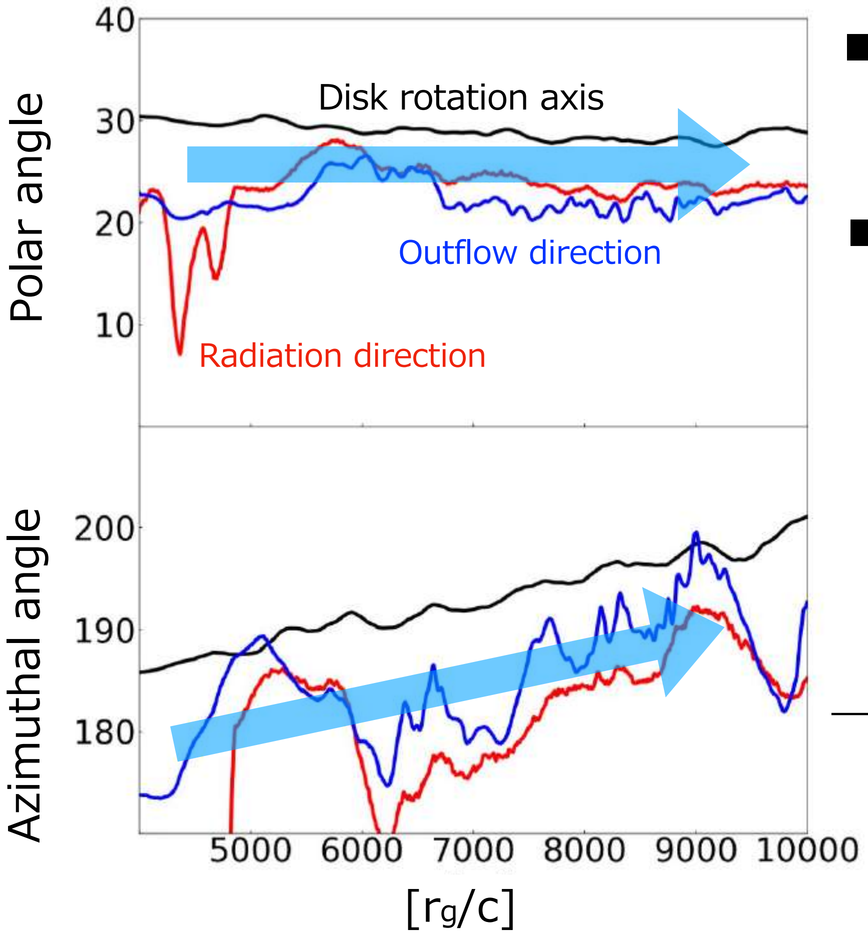
- The tilt angle of the outer region is ~30°, which is determined by the initial setting of the torus.
- The disk is gradually tilted as it approaches the black hole, except for the region of $r<5r_g$.
- The precession angle increases as it approaches the BH.





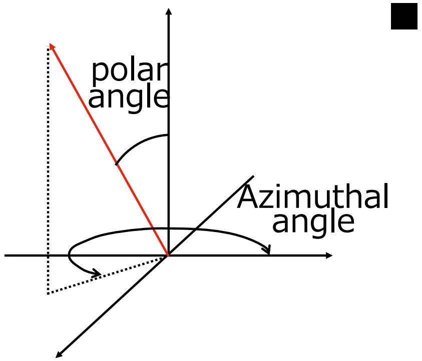
Schematic picture of twisted, tilted disk

# Precession of disk, outflow, radiation



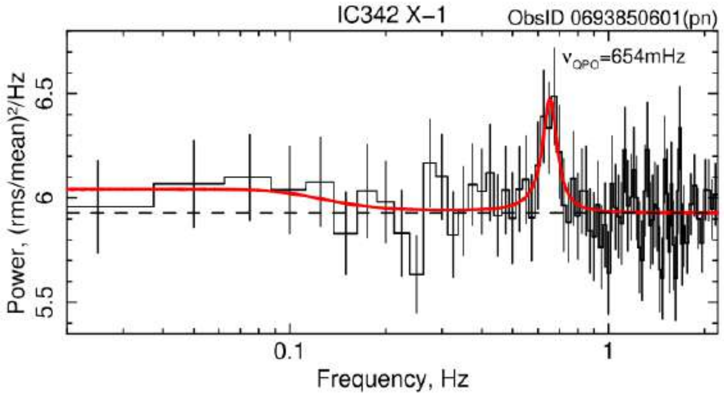
- The super-Eddington disk exhibits the precession motion.

- 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°).

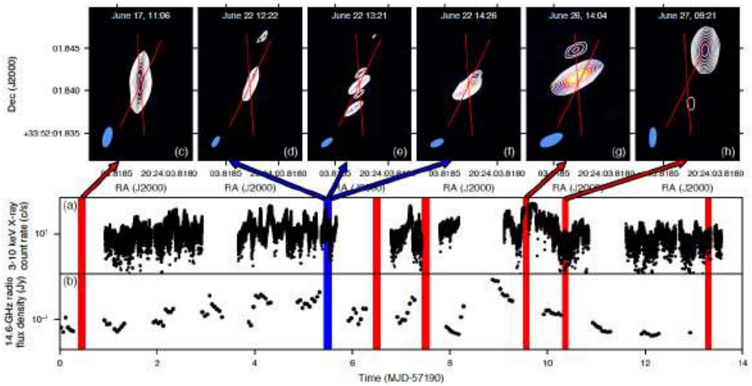


- The direction of outflow and radiation also changes according to the precession motion of the disk.

# Comparison with observations



[1] Quasi periodic oscillations of ULXs:
The typical timescale of the precession is ~ several sec for the case of stellar mass BH and disk size is a few 10rg. This timescale is consistent with the QPOs observed in some ULXs (0.01-1Hz, Atapin 2019).

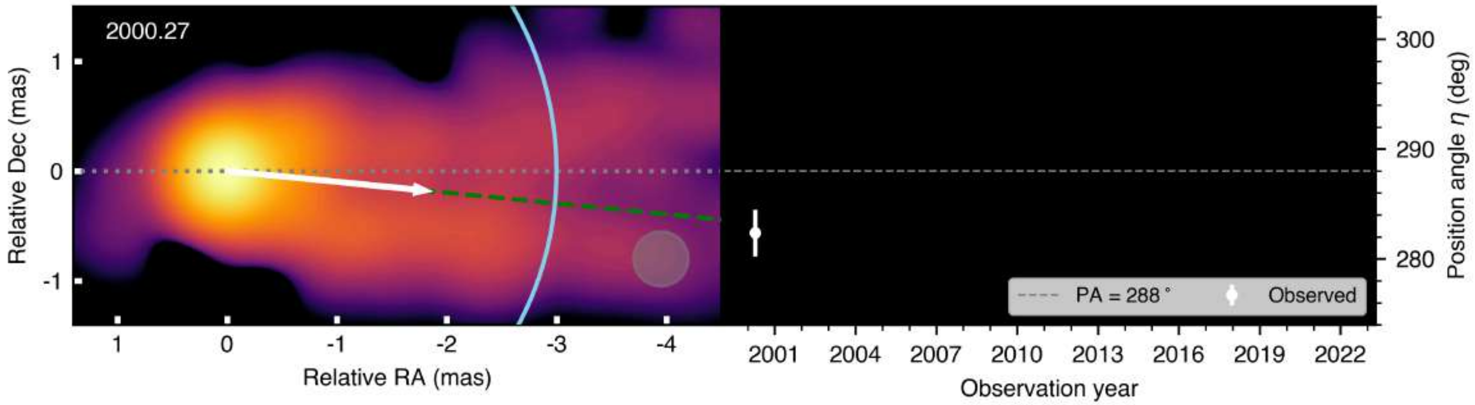


[2] Precession of jets in V404 Cygni:
The direction of jet is changing with time in V404 Cygni (a few min ~ a few hours, Miller-Jones et al. 2019).
Such behavior maybe reproduced if the disk size is a few 100rg.

# Lense-Thirring Precession of RIAF Cui et al. 2023

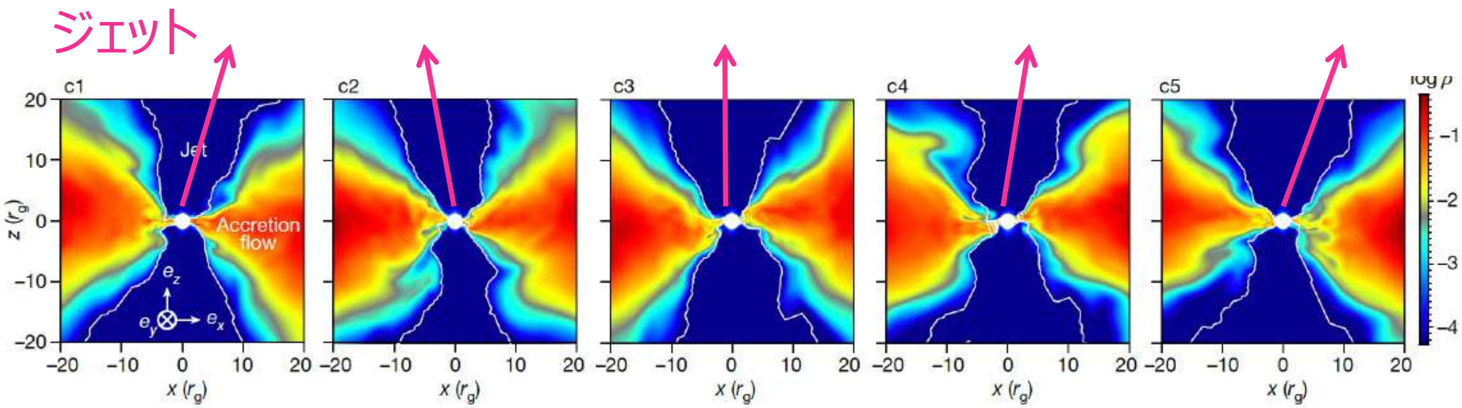
電波観測：

M87のジェットの方向が周期的に変わることを発見



一般相対論的~~輻射~~磁気流体

シミュレーション：



# Super-Edd. Flows around magnetized NSs

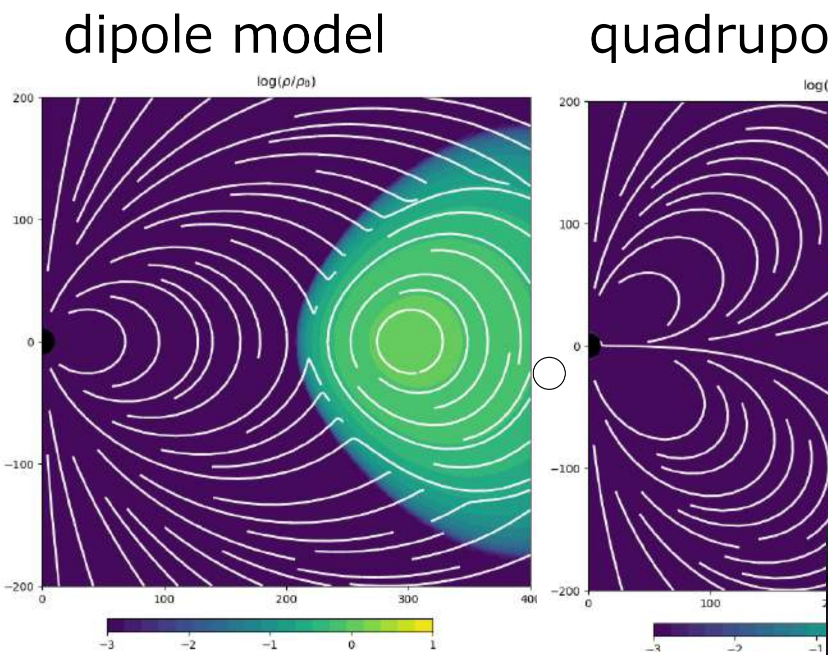
Inoue et al. 2023, Inoue et al. in prep.

**Code**

- 2D General relativistic Radiation-MHD simulation code

**Setup**

- NS: 1.4Msun, 10km
- Magnetic field: Bdip/(Bdip+Bqua)=1, 0.75, 0.5, 0.25, 0
- Initial condition: equilibrium torus with embedded poloidal magnetic field (plasma-beta=100)

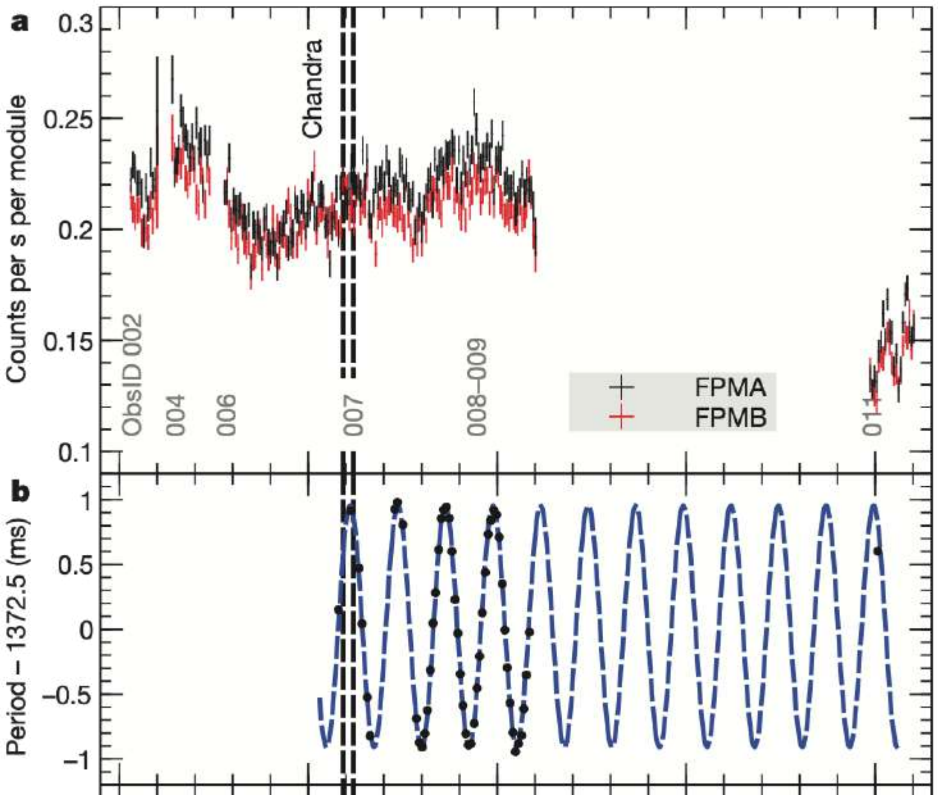

dipole model

quadrupole model

Initial Conditions:
Density & magnetic fields

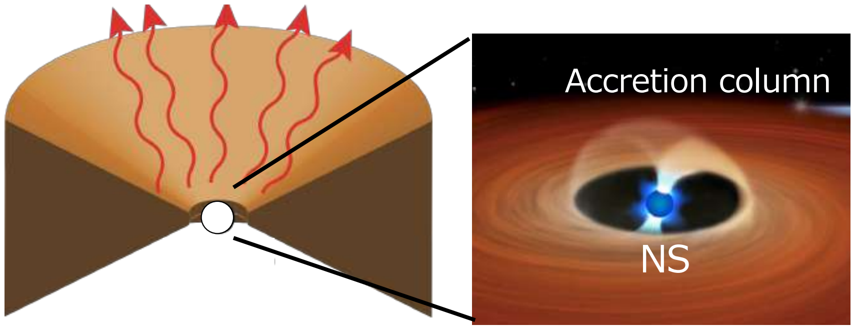

井上壮大さん（筑波大→阪大）

# ULX Pulsars



**NS + Super-Eddington flow**

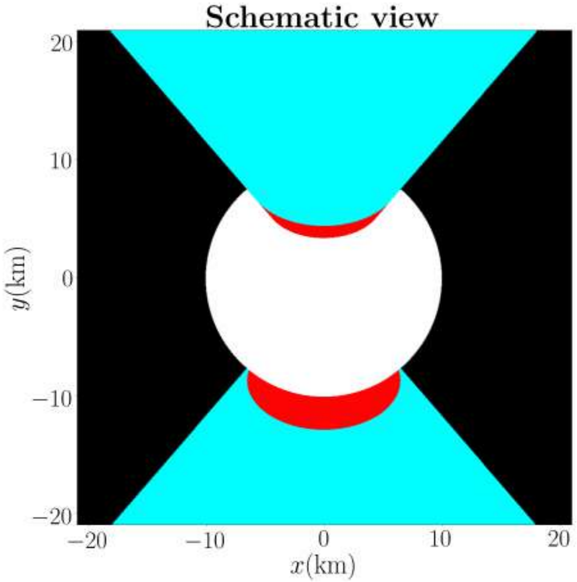
If the central objects of ULXs are NSs, super-Eddington is necessary because the mass of NSs is a few Msun.

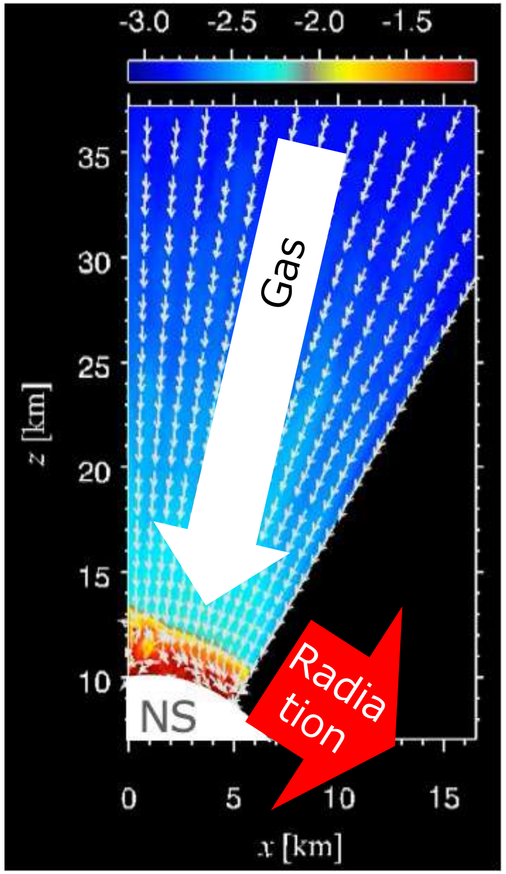


Basko & Sunyaev 76; Ohsuga 07; Mushtukov+15, 18; King & Lasota 16; Kawashima et al. 16; Takahashi & Ohsuga 17, 18; Chashkina+17

# Accretion column

The radiation energy escapes from the side face of the accretion columns. The side face is likely the origin of the X-ray pulse.



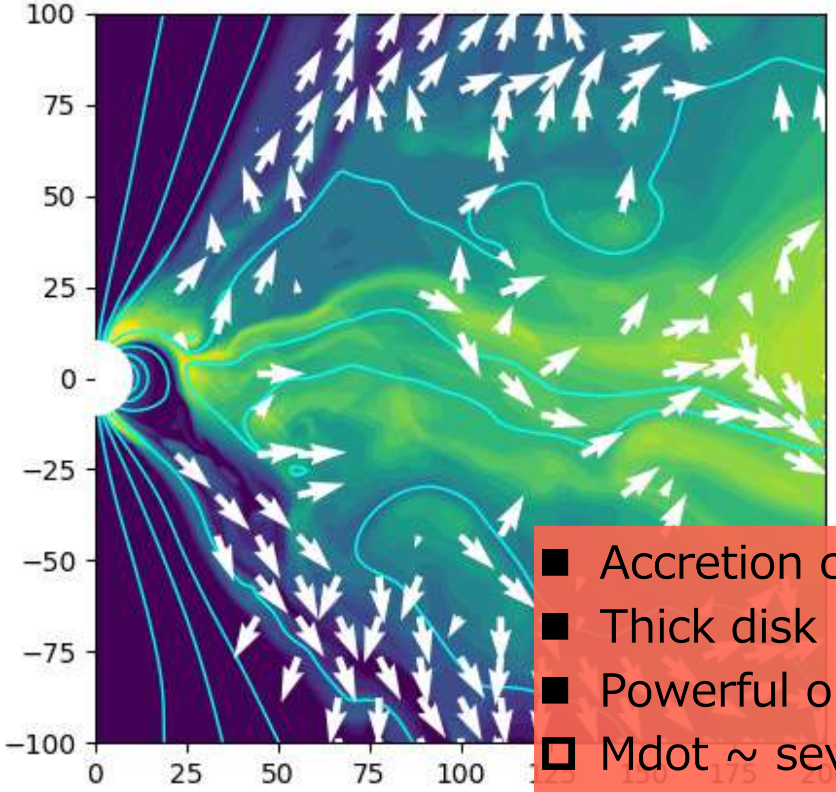


Radiation energy is released from the side surface of the column.

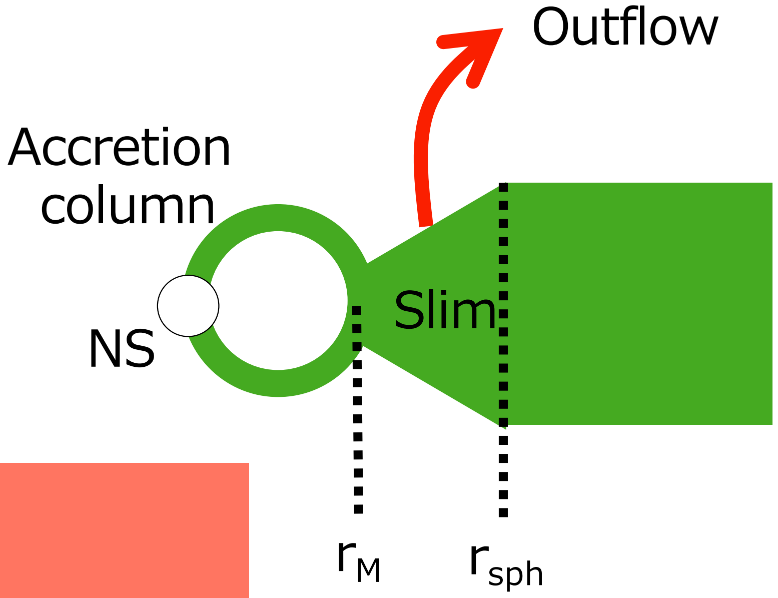
Kawashima et al. 2016

see also
Basko & Sunyaev (1976)
Meszaros (1998),
Mushtukov et al. (2015),
Zhang et al. (2023),
Abolmasov et al. (2023)

# Dipole-dominated case



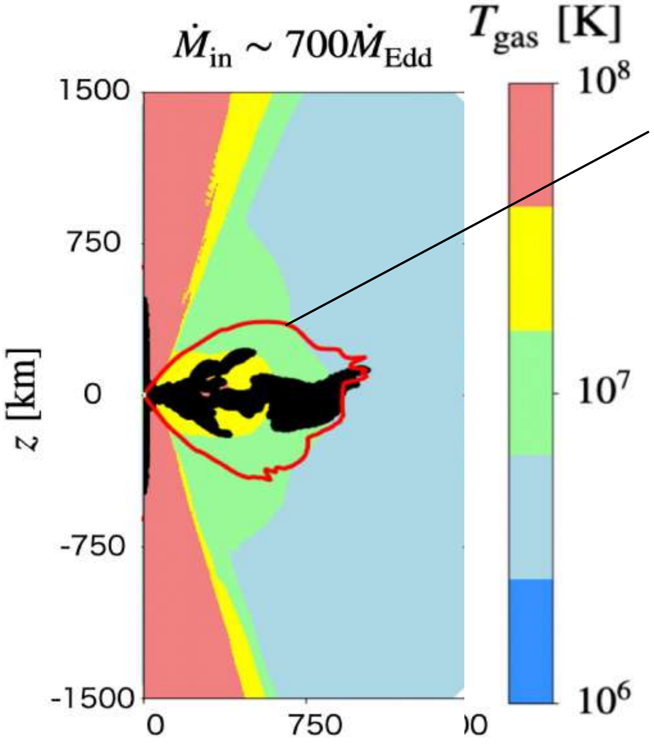
- ■ Accretion columns
- ■ Thick disk
- ■ Powerful outflows
- ☐ Mdot ~ several 100Ledd/c²
- ☐ Luminosity ~ several 10 Ledd



see also
Chashkina et al. 2017, 2019
Abarca et al. 2021

# ULXP Swift J0243.6+6124

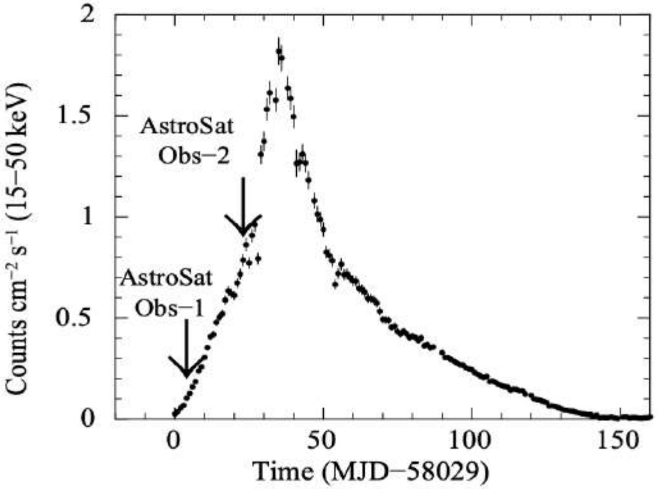
Transient ULXP

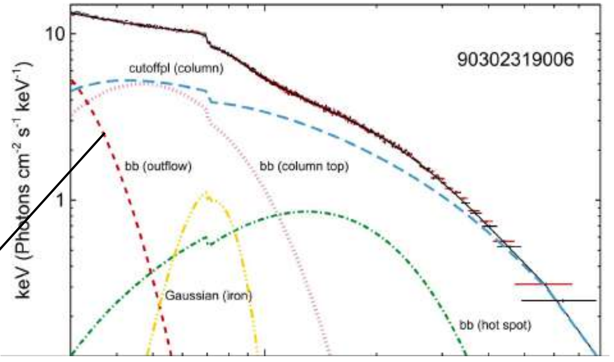


Photosphere of the outflows:
Size: a few 100km
Temperature: ~0.5 keV

⬇

The observed blackbody radiation can be explained.





Black body emission

Tao et al. 2019, Beri et al. 2021

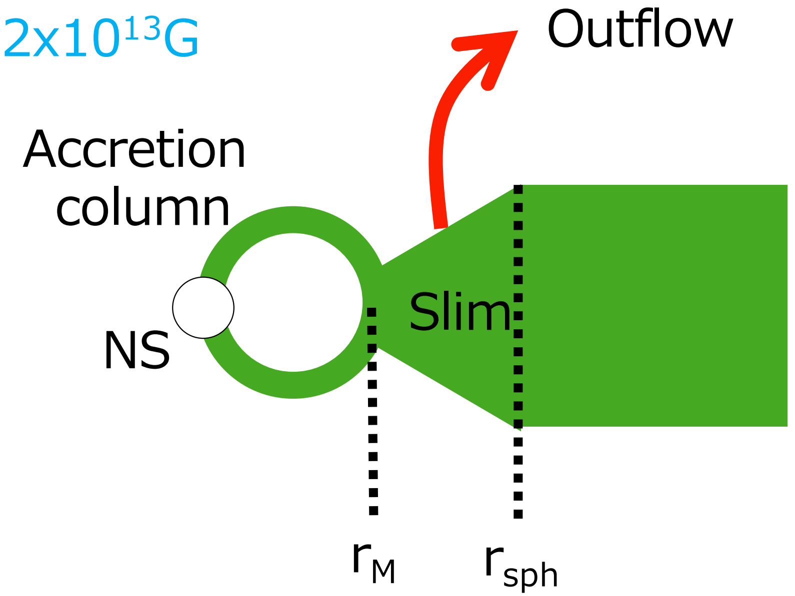
# ULXP Swift J0243.6+6124: magnetic fields

- Pulse period: ~9.8s
- Spin-up rate: $6.8\times10^{-9}\,\mathrm{ss}^{-1}$ (obs 1), $1.8\times10^{-8}\,\mathrm{ss}^{-1}$ (obs 2), $2.2\times10^{-8}\,\mathrm{ss}^{-1}$ (obs 3)
- Black Body emission（T~0.5keV and R~100-500km) is detected in two observations and not in one observation
- Cyclotron resonance scattering feature: $\sim2\times10^{13}$G

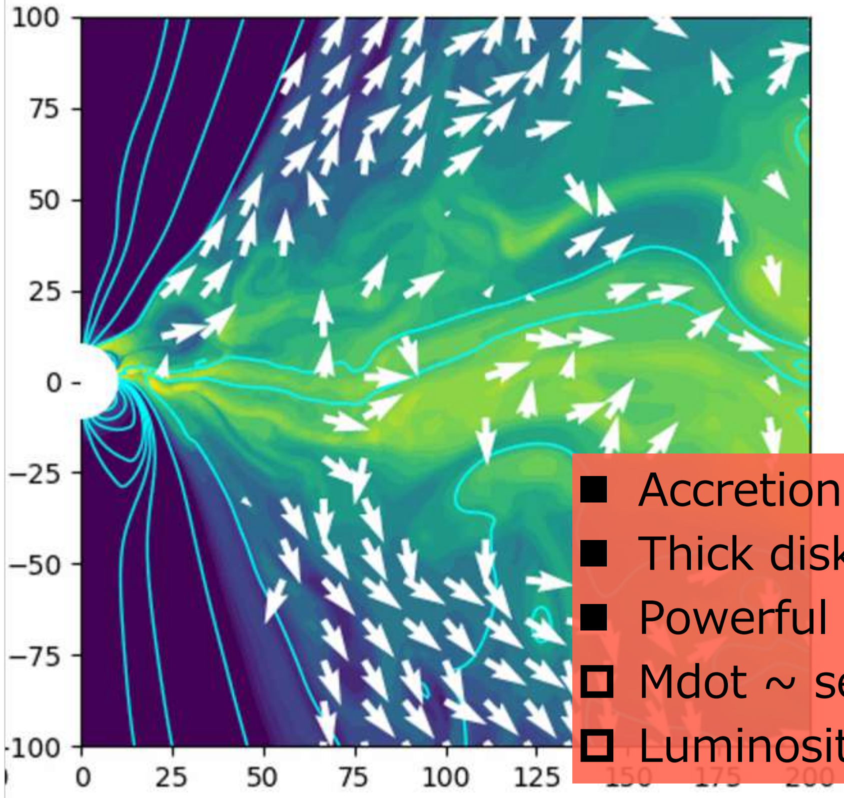
⬇

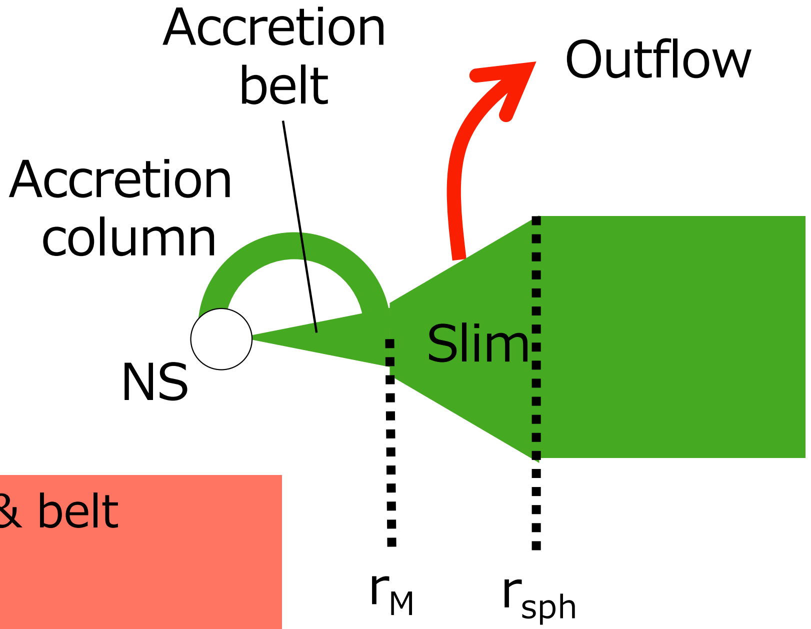
Dipole fields

$\sim 3\times10^{11}$G - $4\times10^{12}$G



# Quadrupole-dominated case





■ Accretion column & belt
■ Thick disk
■ Powerful outflows
□ Mdot ~ several 100Ledd/$c^2$
□ Luminosity ~ several 10 Ledd

# ULXP Swift J0243.6+6124: magnetic fields

- ■ Pulse period: ~9.8s
- ■ Spin-up rate: $6.8\times10^{-9}ss^{-1}$ (obs 1), $1.8\times10^{-8}ss^{-1}$ (obs 2), $2.2\times10^{-8}ss^{-1}$ (obs 3)
- ■ Black Body emission（T~0.5keV and R~100-500km) is detected in two observations and not in one observation
- ■ Cyclotron resonance scattering feature: ~$2\times10^{13}$G

Quadrupole fields ~ $2\times10^{13}$G ← Cyclotron resonance scattering

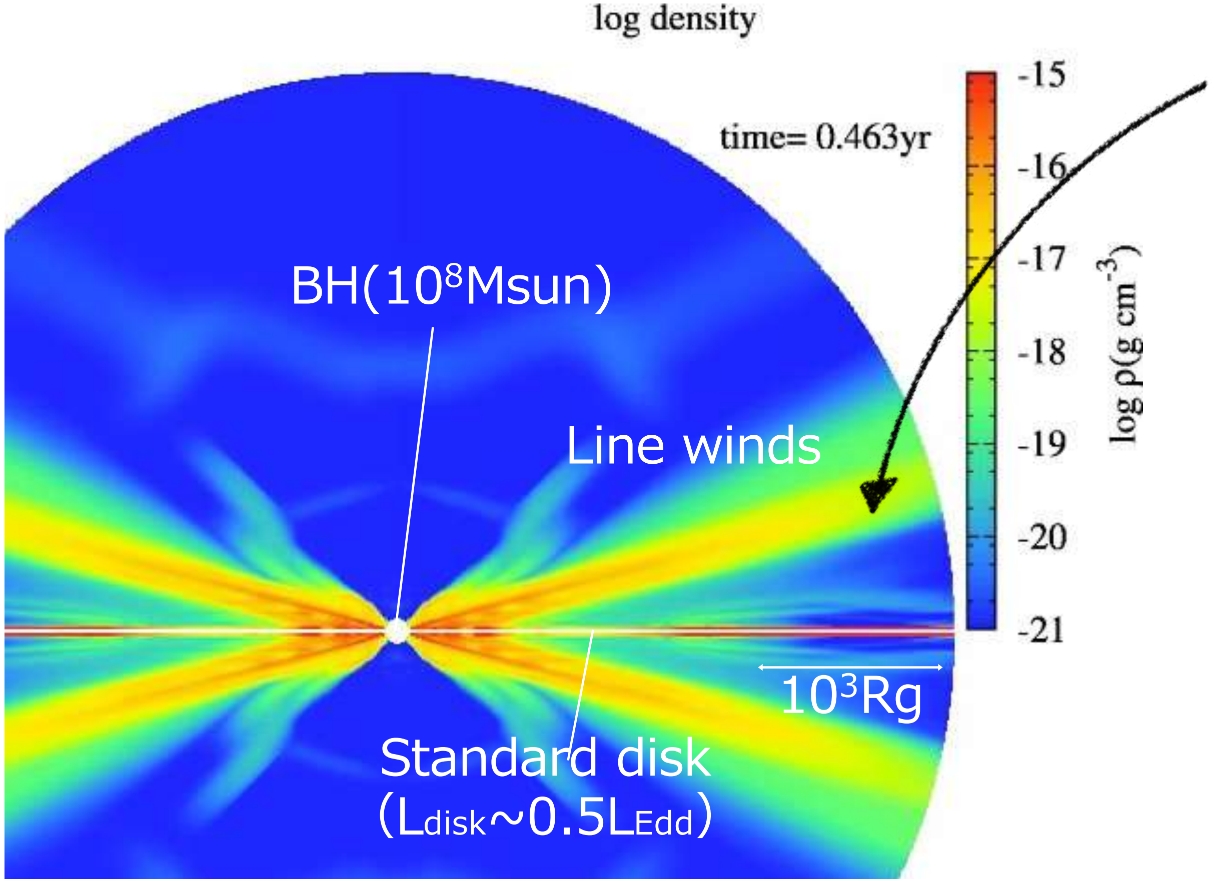
Dipole fields < $4\times10^{12}$G

↑ If the dipole magnetic field exceeds this value, the magnetospheric radius becomes too large, causing the disappearance of the super-Eddington disk region and preventing the formation of radiatively driven thick winds.

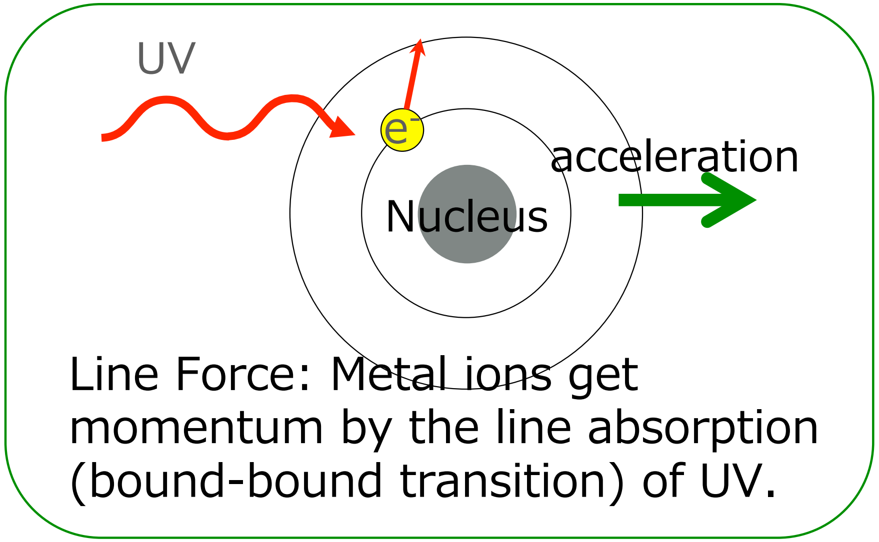
# Simulations of Line Winds

野村真理子さん
（弘前大）

Nomura et al. 2016, 2017, 2020, 2021
(see also Proga et al. 00, 04)



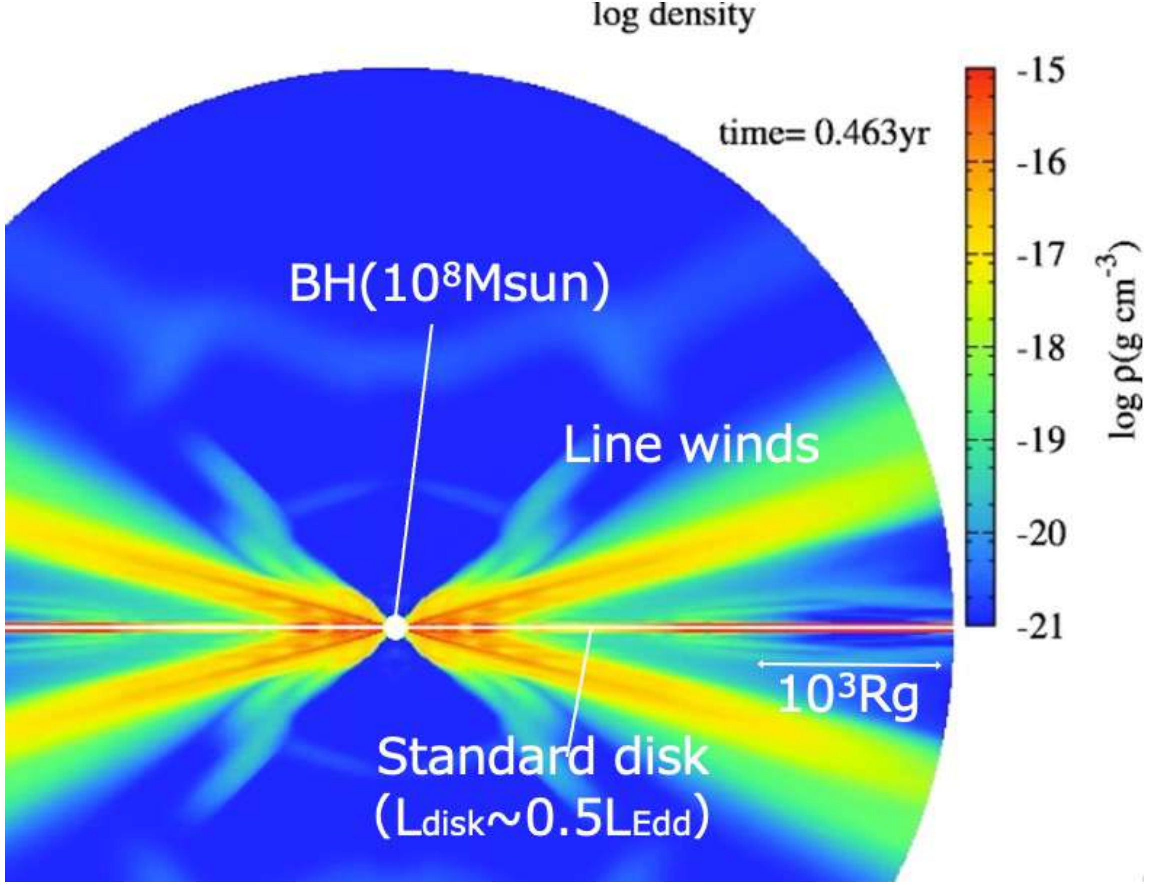
From the standard disk, the disk wind is launched by the radiation force for spectral lines (line-force).



Line Force: Metal ions get momentum by the line absorption (bound-bound transition) of UV.

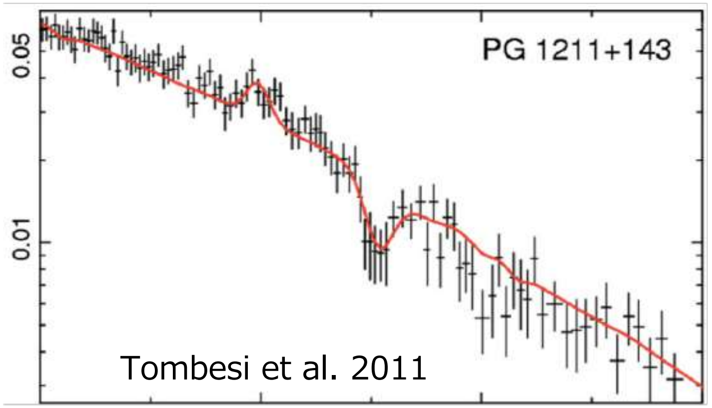
# Simulations of Line Winds

Nomura et al. 2016, 2017, 2020, 2021
(see also Proga et al. 00, 04)



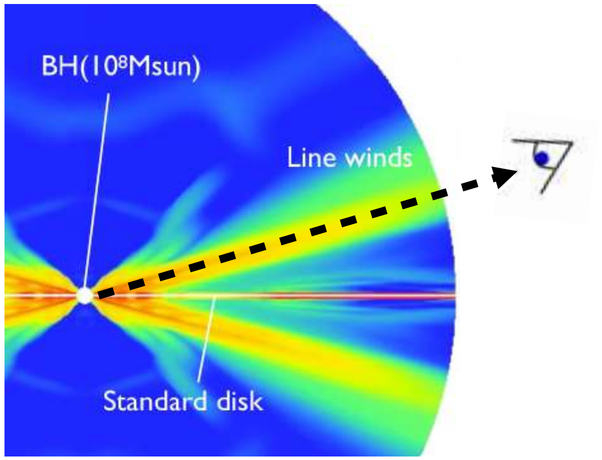
Ultra Fast Outflows (UFOs) are detected in some Sy galaxies. Line-driven winds (~0.1c) are one of the plausible model.

Observed absorption lines

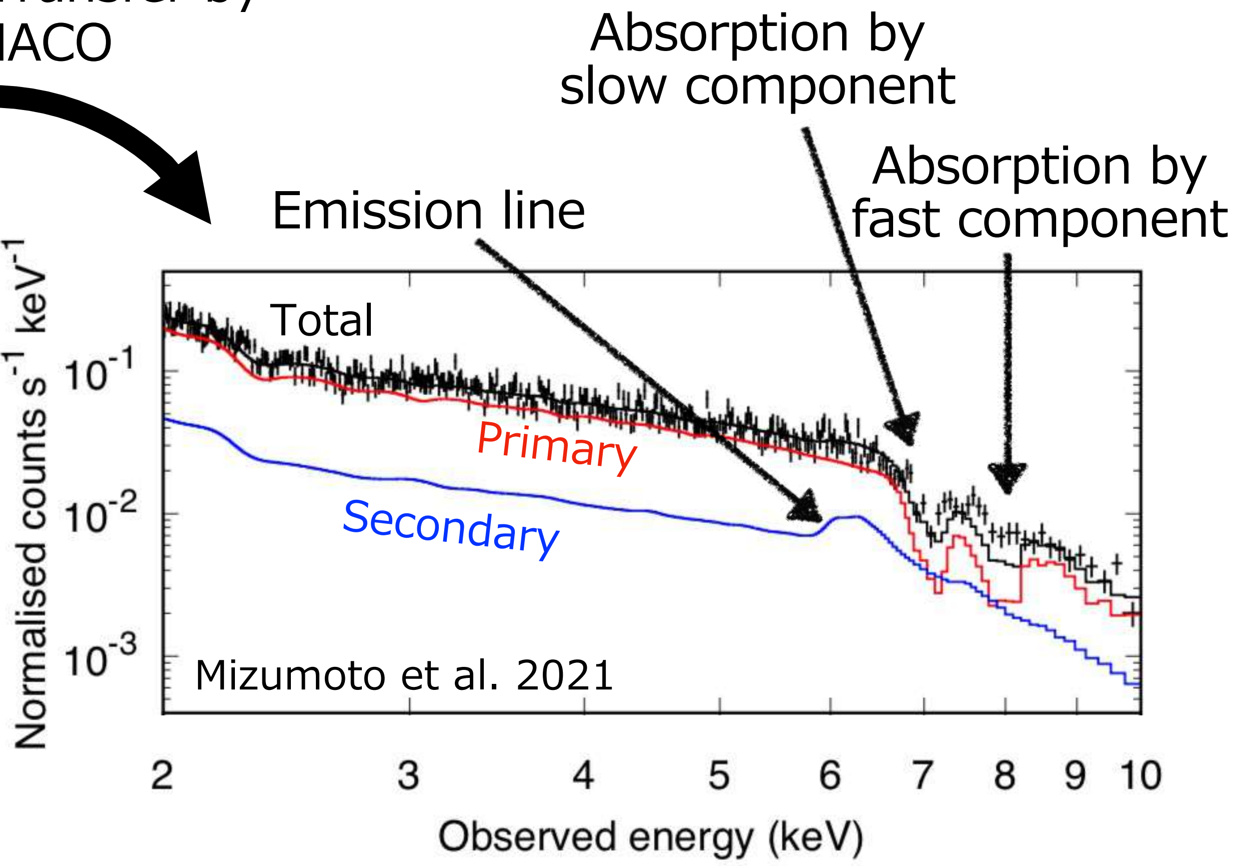


Tombesi et al. 2011

# Comparison with UFOs (PG 1211+143)

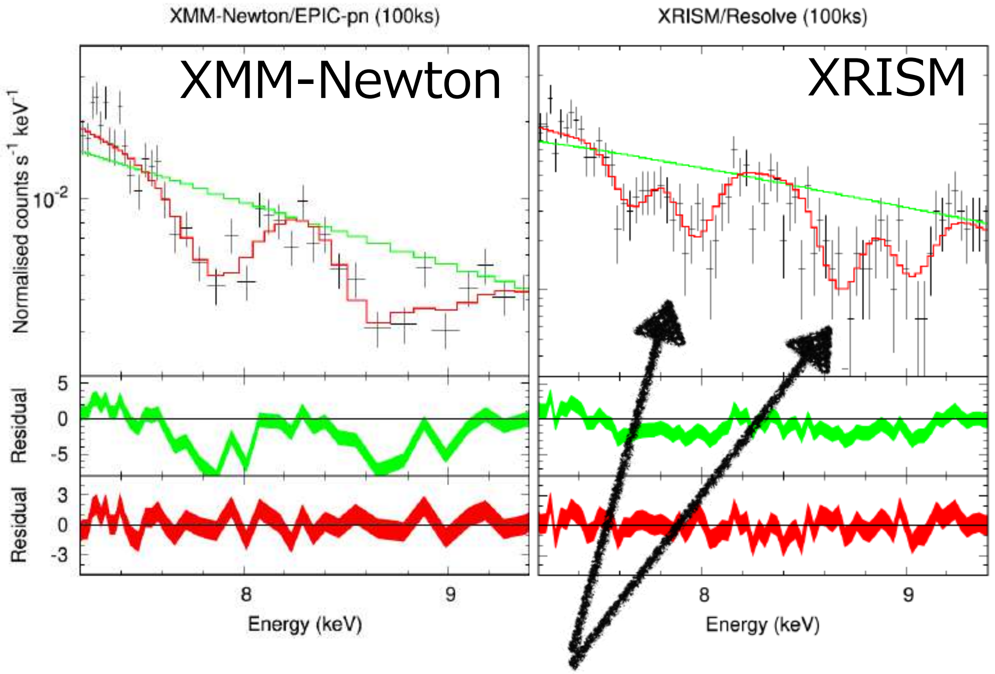


Radiation Transfer by MONACO



- There are some absorbing regions along the line of sight.
- X-ray spectrum (two absorption lines and emission line) can be well described by our model.

# Future observations



Absorption lines from H-like and He-like iron are resolved by XRISM.

A more detailed comparison with observations by XRISM provides a more accurate understanding of the disk wind structure.

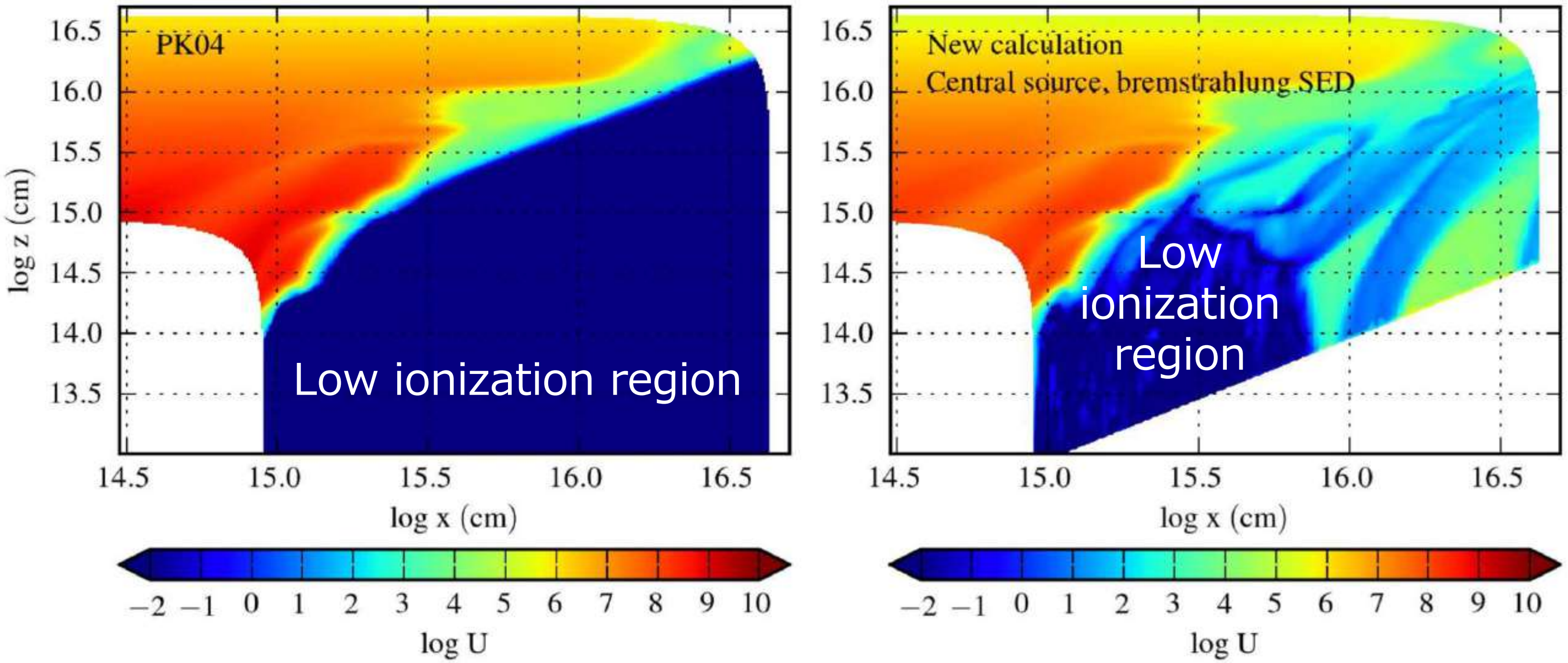
Good news. Our proposal was accepted last week

乞うご期待！

# Does a line wind not occur !?

Higgnbottom et al. 2014

Ionization parameter



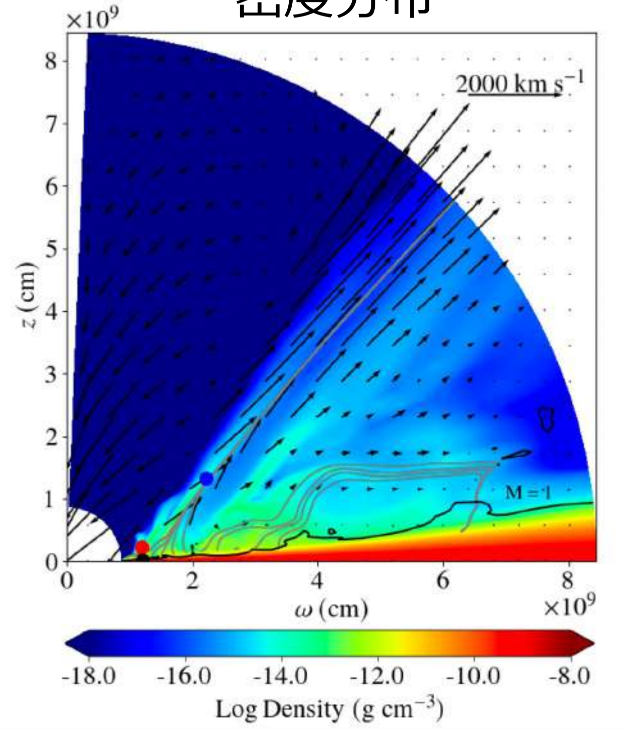
Low ionization region

Low ionization region

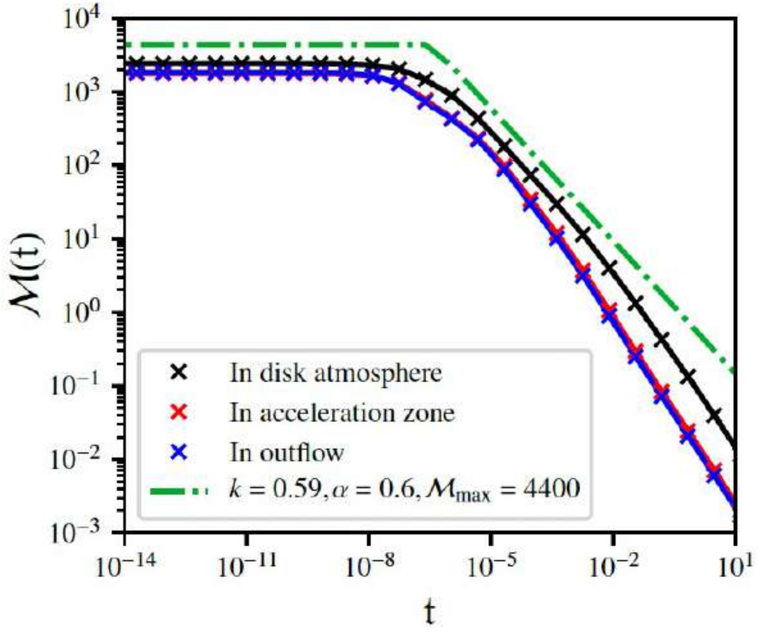
Conventional calculation methods underestimate the degree of ionization → overestimate the force multiplier.

# Does a line wind not occur !? Higgnbottom et al. 2023

密度分布



Force multiplier



WDの降着円盤でLine windのモンテカルロ輻射流体計算を実施

モンテカルロ輻射輸送計算を実施したところ, 従来の方法よりForce multiplierが小さくなり, 質量噴出率は２桁低下.

# Does a line wind not occur !?

Higgnbottom et al. 2014

ISSI workshop (2024.6)でのShane Davis氏のスライド

X線領域の（ちょっとマイナーな）lineを組み込んでみたら, AGNの場合に限っては質量噴出率が２桁増加

Line windは強いのか弱いのか？
私も小高氏（阪大）と組んで参戦予定

# 「富岳」成果創出加速プログラム

**森脇可奈**
**（東京大）**

全国31の研究機関
参加者合計92名（女性8名）

**代表機関**

筑波大学
計算科学研究センター・大須賀 健

**AI班**

**協力機関**：
東京大学, 筑波大学, 名古屋大学,
神戸大学, 理化学研究所

## サブ課題Ａ

**大規模数値計算とAIの融合による宇宙の進化史の解明**

宇宙大規模構造・銀河

**協力機関**：
東京大学, 千葉大学, 筑波大学

**連携機関**：
京都大学, 北海道大学,東北大学,
神戸大学,松江高専

**藤井通子**
**（東京大）**

## サブ課題Ｂ

**大規模シミュレーションで挑む星・惑星形成過程の階層横断的研究**

分子雲・星・惑星

**協力機関**：
東北大学, 国立天文台, 北海道大学,
岡山大学

**連携機関**：
東京工業大学,大阪大学,東京大学,
神戸大学,京都女子大,名古屋大学

**富田賢吾**
**（東北大）**

## サブ課題Ｃ

**ブラックホールと中性子星を核にした爆発的天体現象の解明**

超新星爆発,
ブラックホール, 中性子星

**協力機関**：
国立天文台,千葉大学,早稲田大学,
沼津高専,東邦大学,京都大学

**連携機関**：
駒澤大学, 弘前大学, 東京大学, 九州大学, 東北大学, 福岡大学, KEK, 他

**滝脇知也**
**（NAOJ）**

## サブ課題Ｄ

**恒星活動の多様性と惑星環境のダイナミクスの解明**

恒星活動・惑星環境

**協力機関**：
名古屋大学, 神戸大学

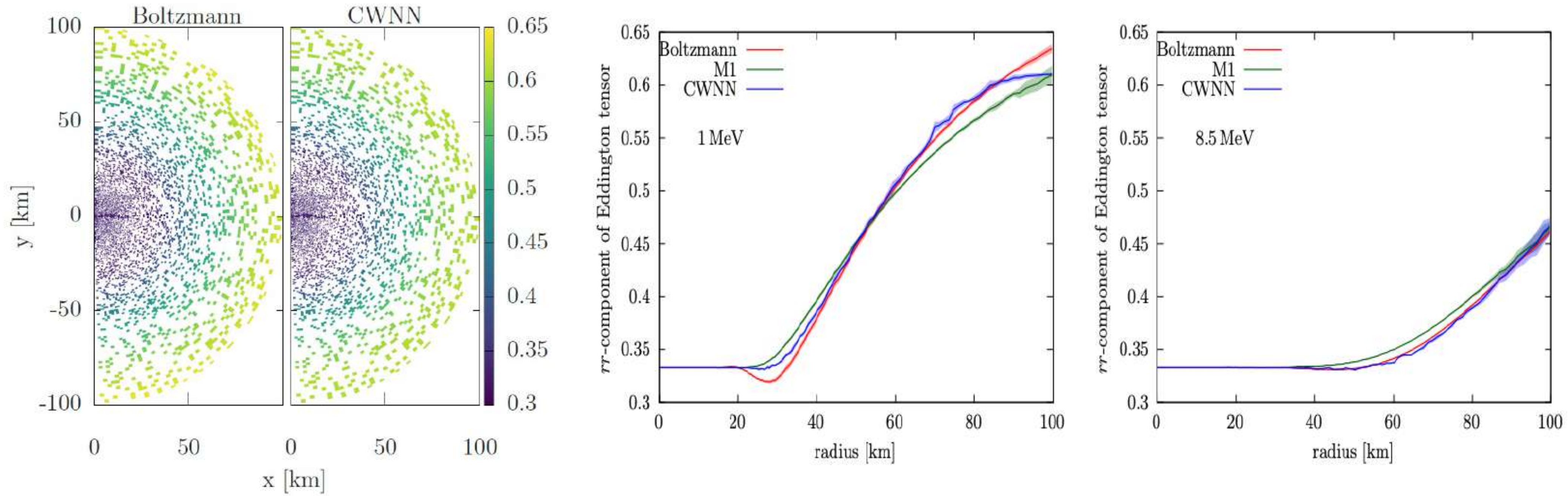
**連携機関**：
東京大学, 京都大学, 国立天文台, 新潟大学, 山形大学,コロラド大学,北海道情報大学,松江高専,東北大学., 九州大学, 他

**堀田英之**
**（名古屋大）**

# Machine Learning of the Edd. tensor

第一原理計算計算の結果を教師データとして機械学習モデル（CWNN）を構築

rr-component of Eddington tensor



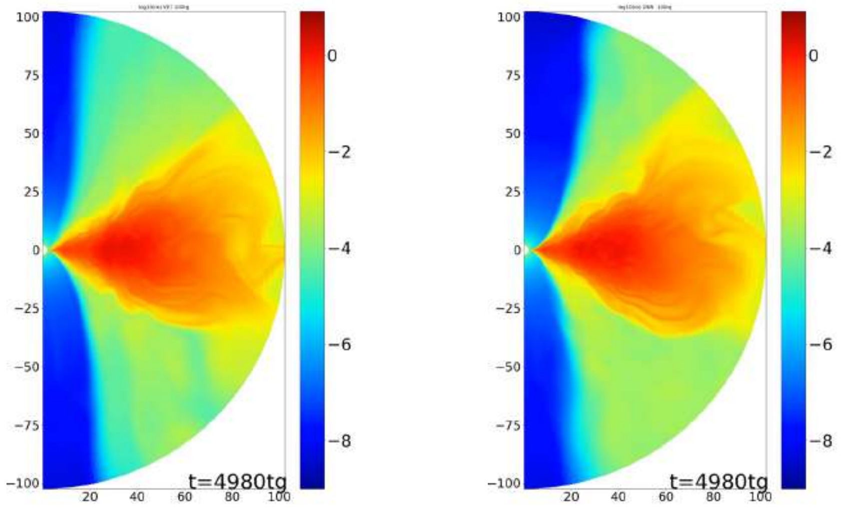
超新星爆発のみなさんは, エディントンテンソルの推定に成功したようです．我々は・・・

# Machine Learning of the Edd. tensor

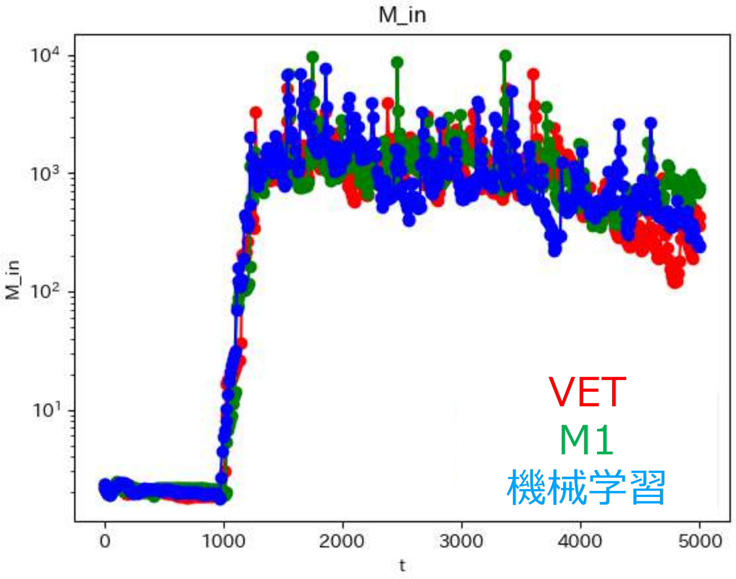
上野君(筑波大M2)

Variable Eddington Tensor法 by 朝比奈 の結果を教師データとして機械学習モデルを構築

密度分布. 左:VET 右:機械学習



質量降着率

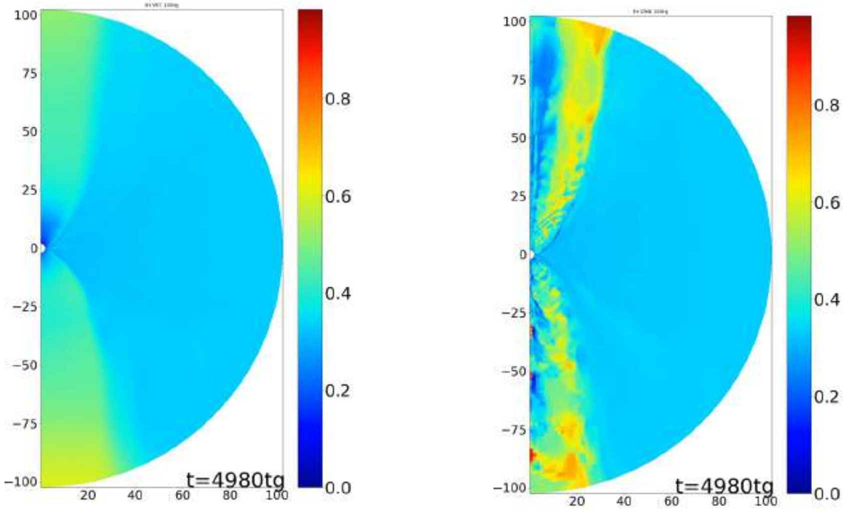


だいたいOKに見えるが・・・

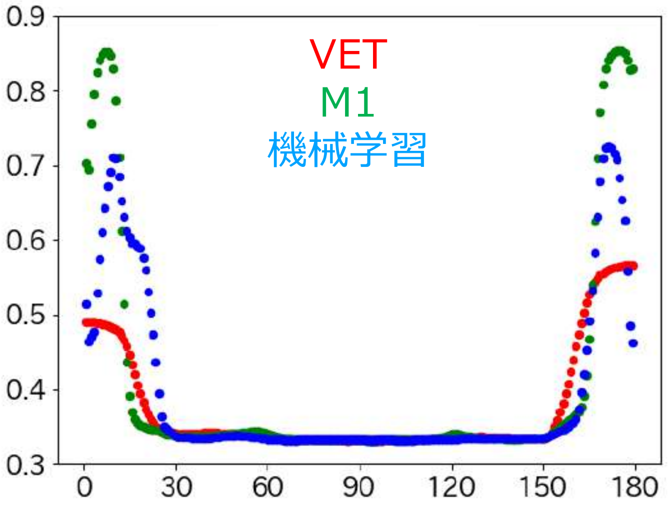
# Machine Learning of the Edd. tensor

Variable Eddington Tensor法 by 朝比奈 の結果を教師データとして機械学習モデルを構築

エディントンテンソルのrr成分.
左:第一原理計算 右:機械学習



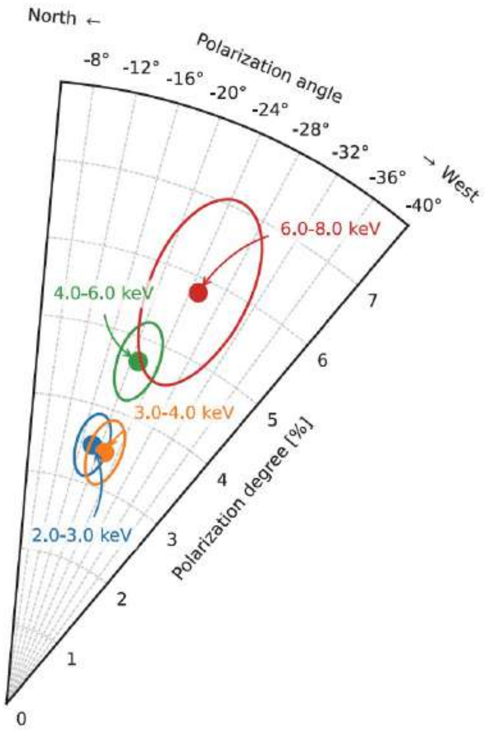
エディントンテンソルの
rr成分の角度布（r=100rg）



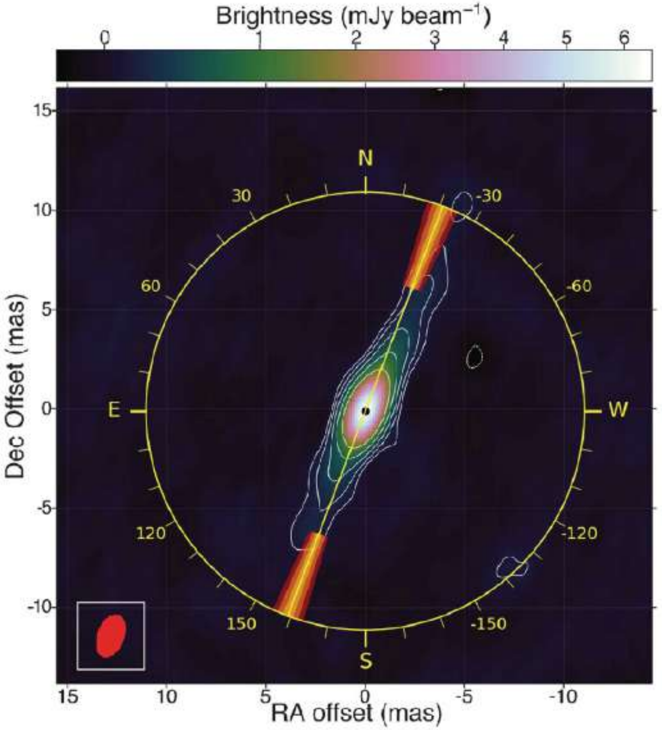
光学的に薄いところで精度が悪い。。。
*現在はこれより少しマシになってます

# X-ray polarization of Cyg X-1 Krawczynski et al. 2022

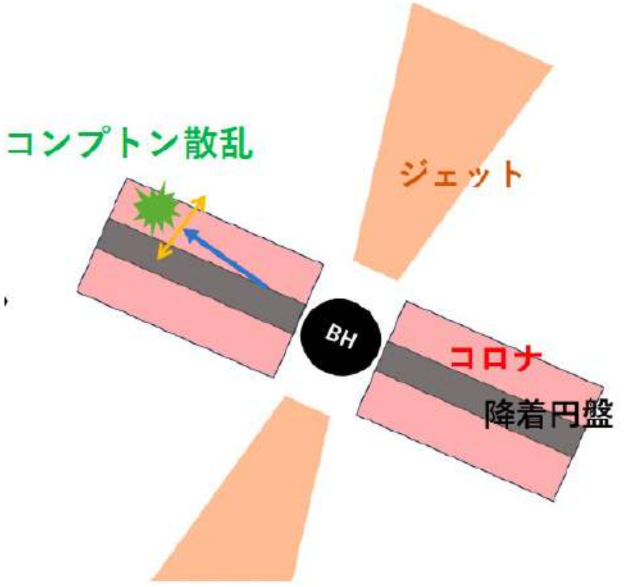
X線偏光の角度



ジェットの方向

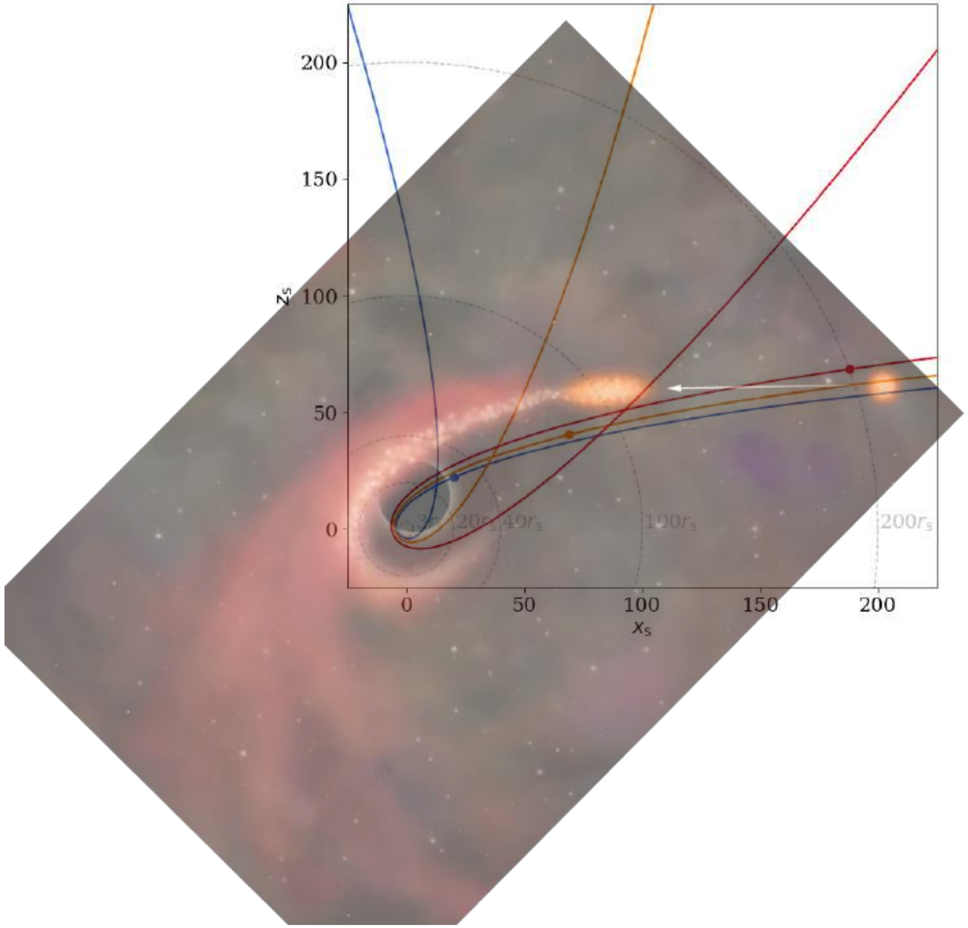


ジェットに垂直（円盤に平行）
なコロナが存在!?
ジェットは散乱体ではない!



ただし,竹林晃大君の修論によると, ジェットが散乱体だったとしてもジェットに平行な偏光を説明できる

# Radiation-MHD for super-Edd. TDE



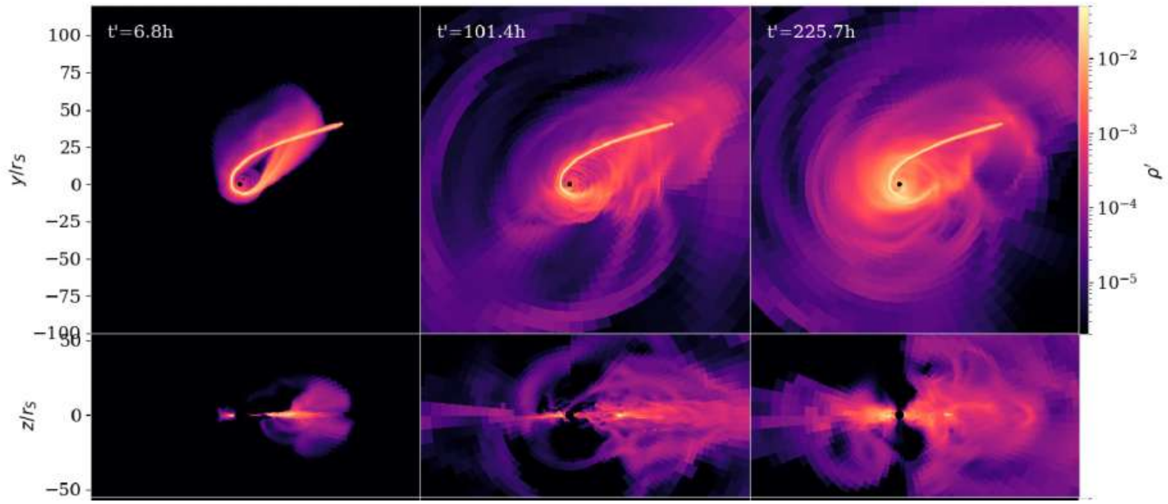
Huang et al. 2024

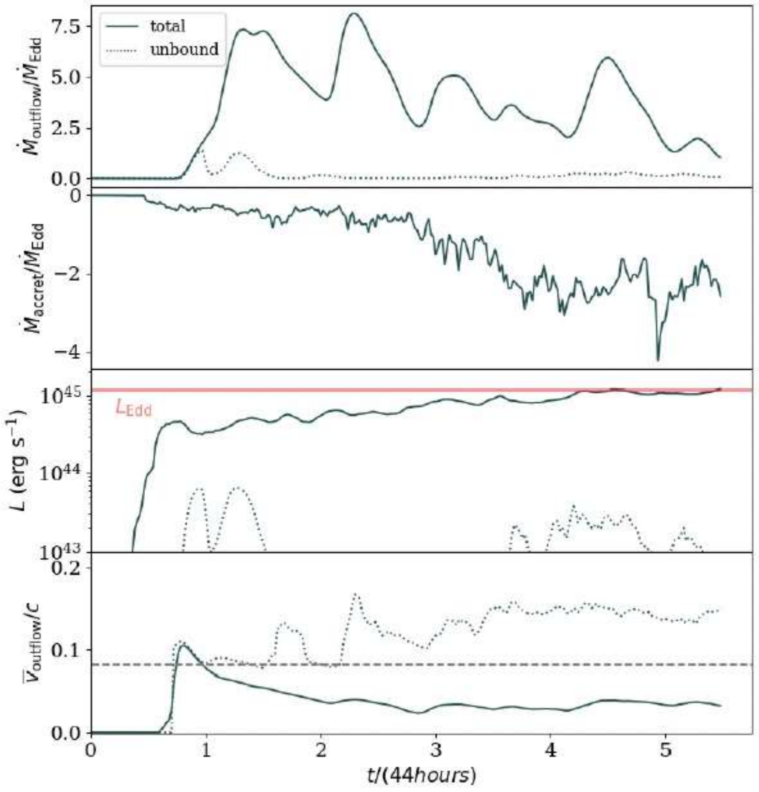
Super-Edd TDEの輻射流体シミュレーション

- 潮汐破壊された星が作るガス流を想定し, ある一点から連続的にガスを流入
- 注入率は10Mdot_Edd

# Radiation-MHD for super-Edd. TDE

密度分布

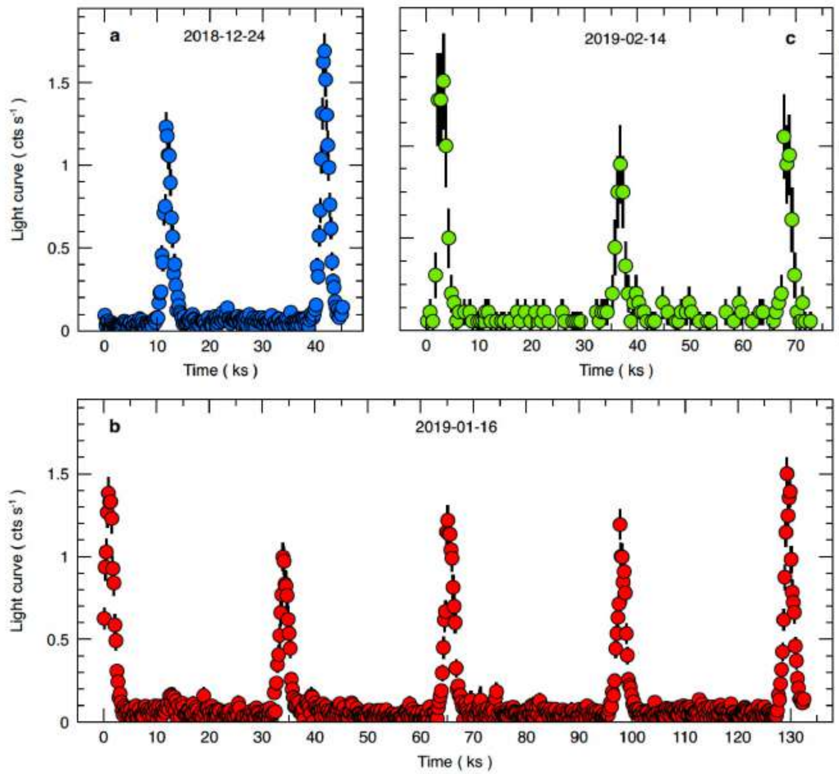




- ■ ストリーム同士が衝突
- ■ Outflow rateはMdot_Eddの数倍
- ■ accretion rateはMdot_Edd以下
- ■ 光度はEddington以下（衝突で光る）

# Quasi-periodic eruption （QPE）

X線の光度変化



G. Miniutti et al. 2019, Nature 573, 381

準周期的にX線が増光する現象

■ 周期：数時間のものが多い

■ 増光：数十倍

■ 天体数：数例

■ メカニズム：不明

□ 円盤不安定

□ 星の部分的潮汐破壊

□ 星と円盤の衝突

□ 円盤の歳差運動

# おわり